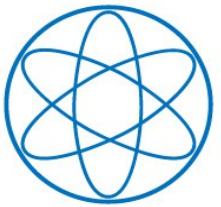
Addressing theoretical uncertainties in direct dark matter searches

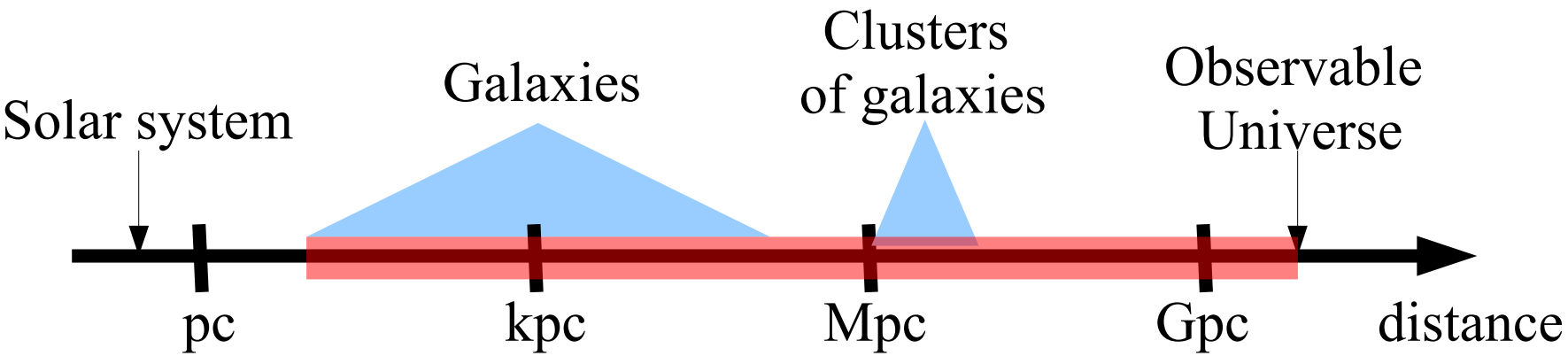
Alejandro Ibarra
Technische Universität München



In collaboration with Andreas Rappelt, arXiv:1703.09168

Hep2018
Valparaiso
January, 2018

There is evidence for dark matter in a wide range of distance scales



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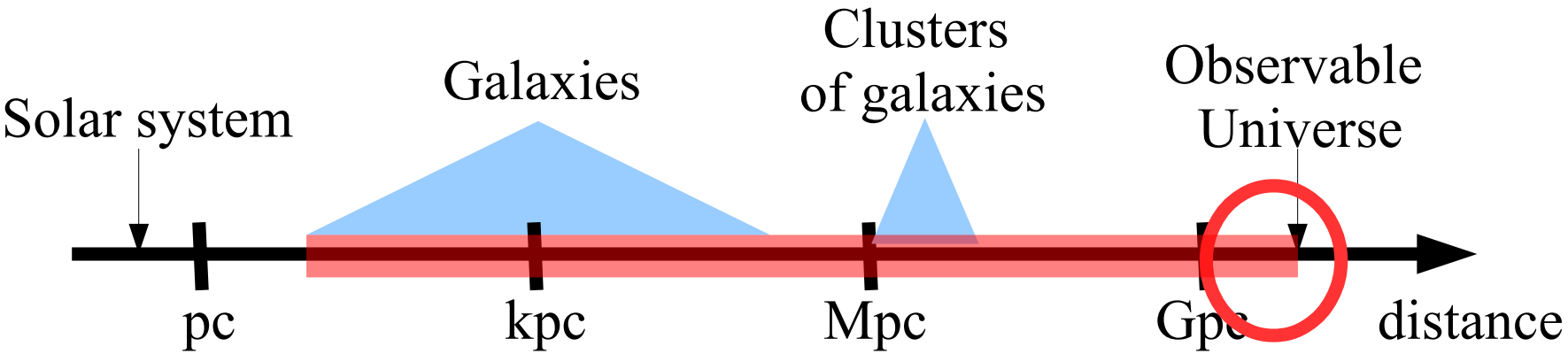

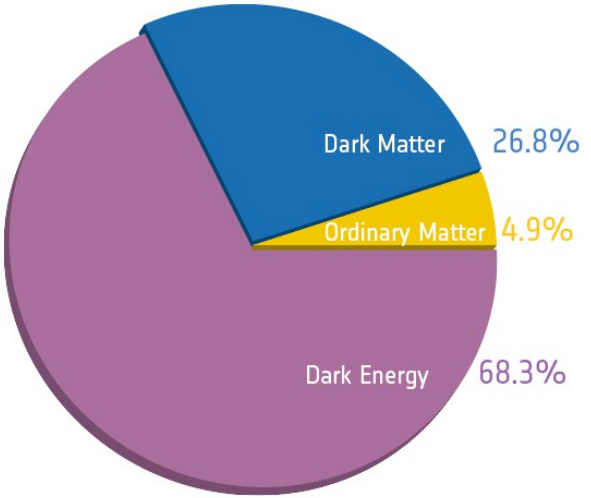

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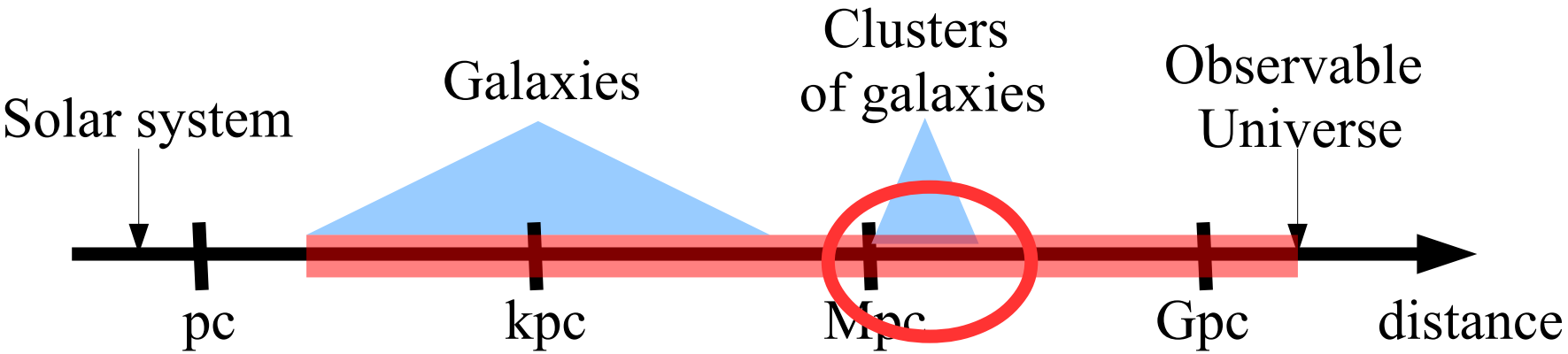

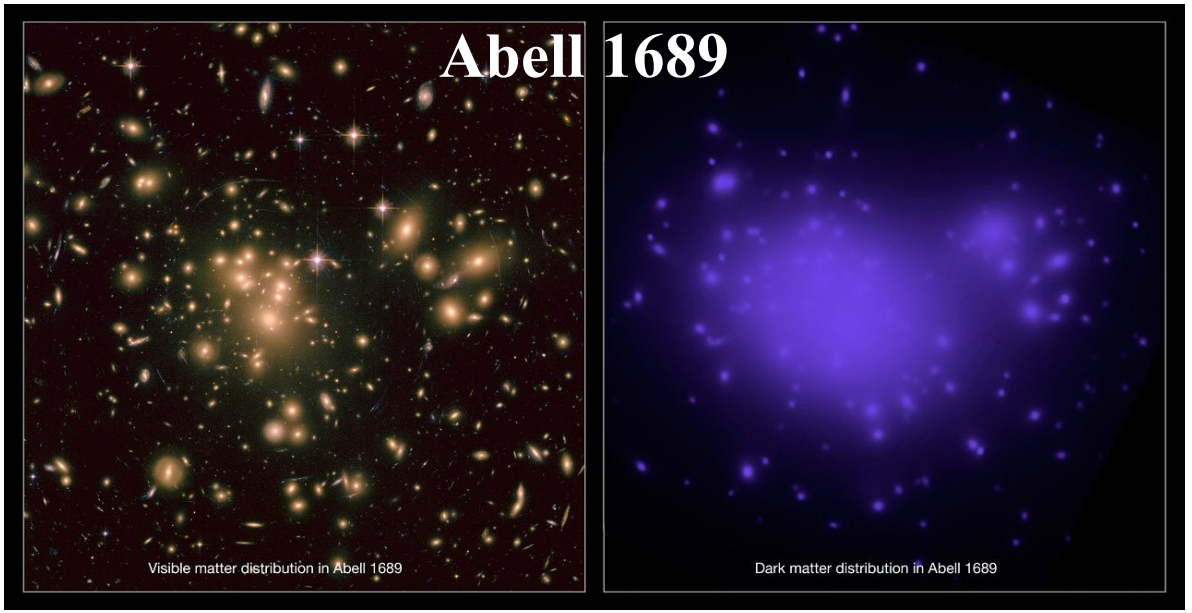

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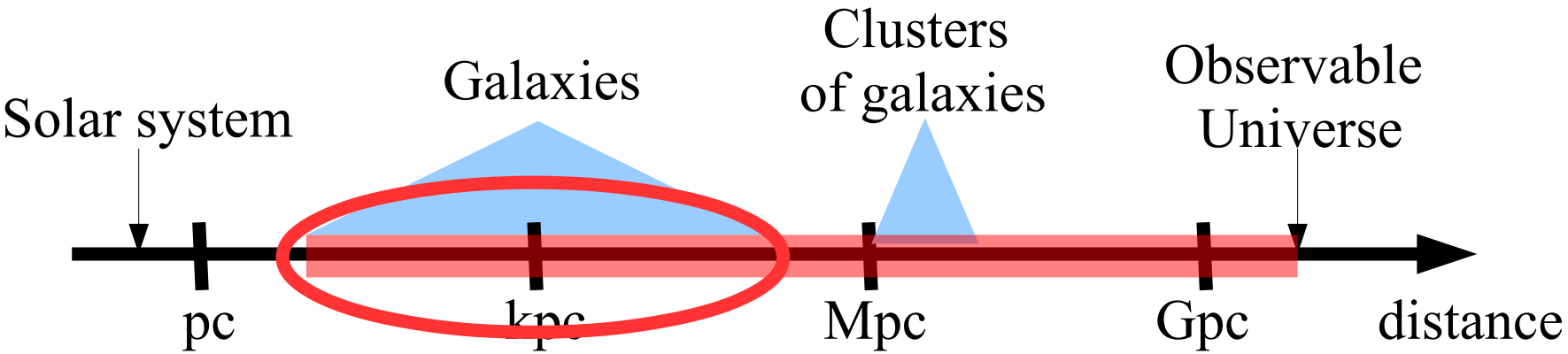

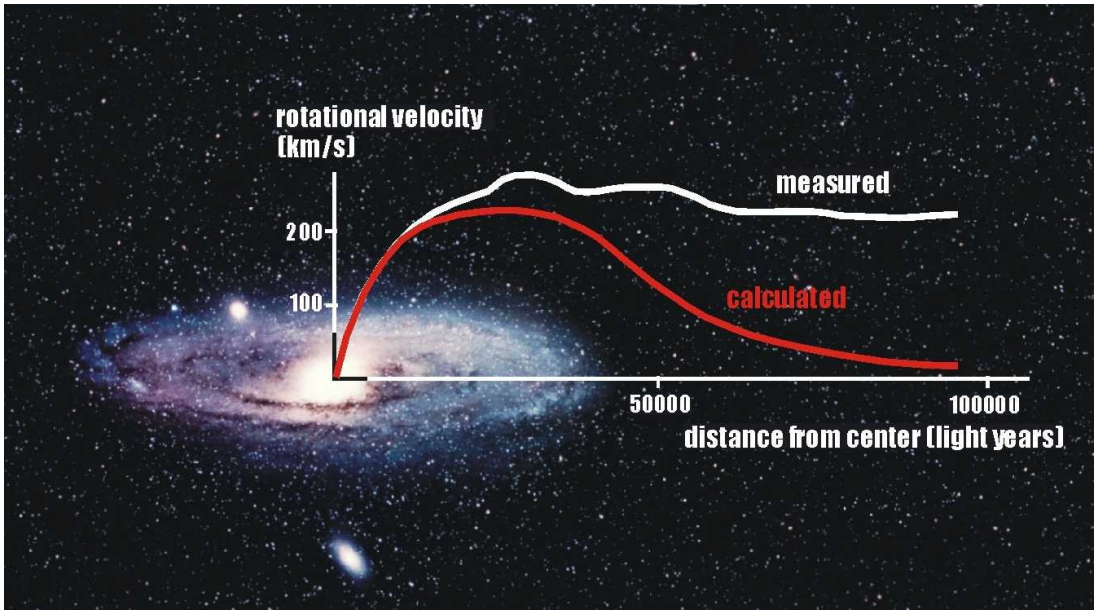

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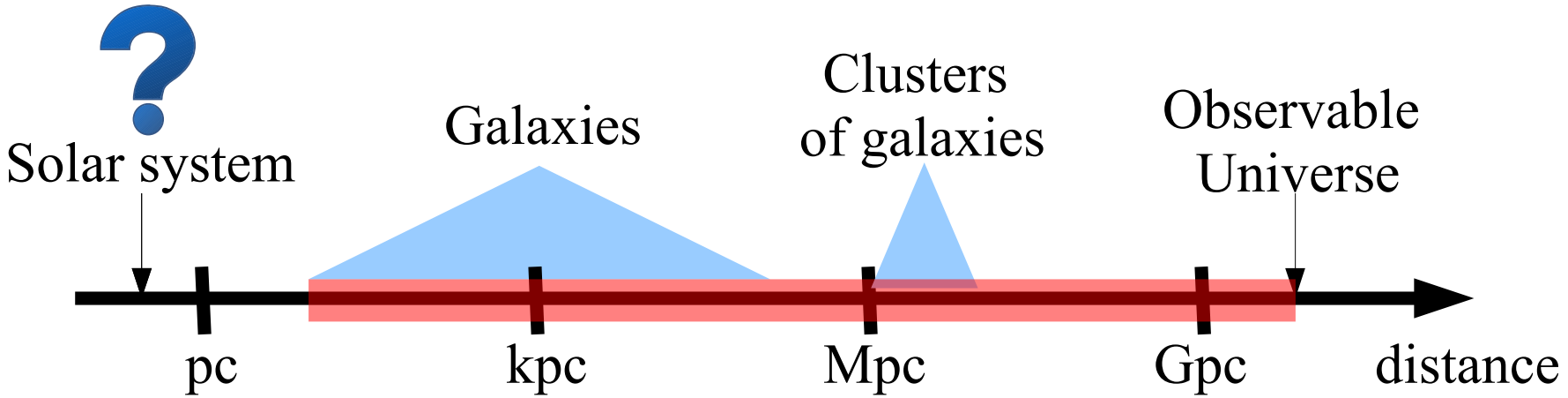

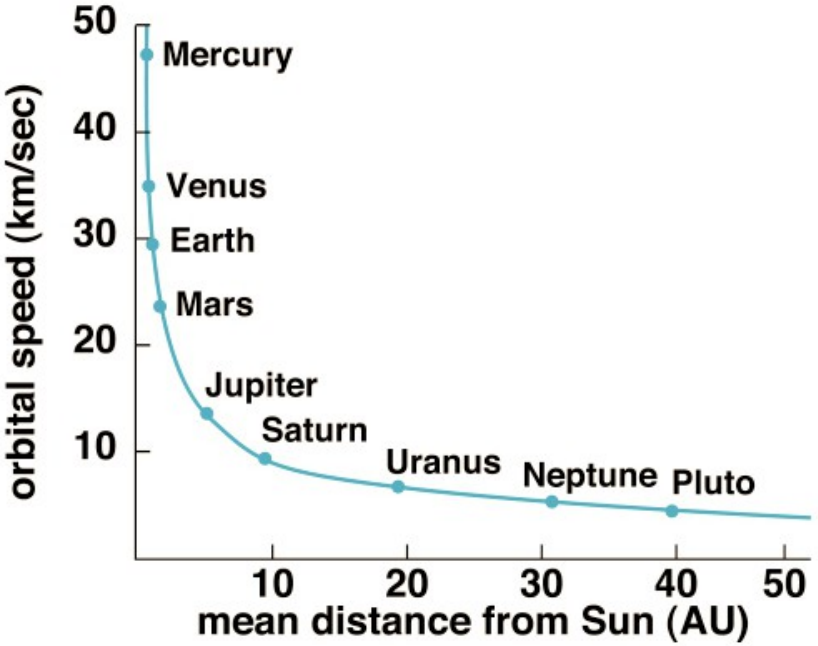

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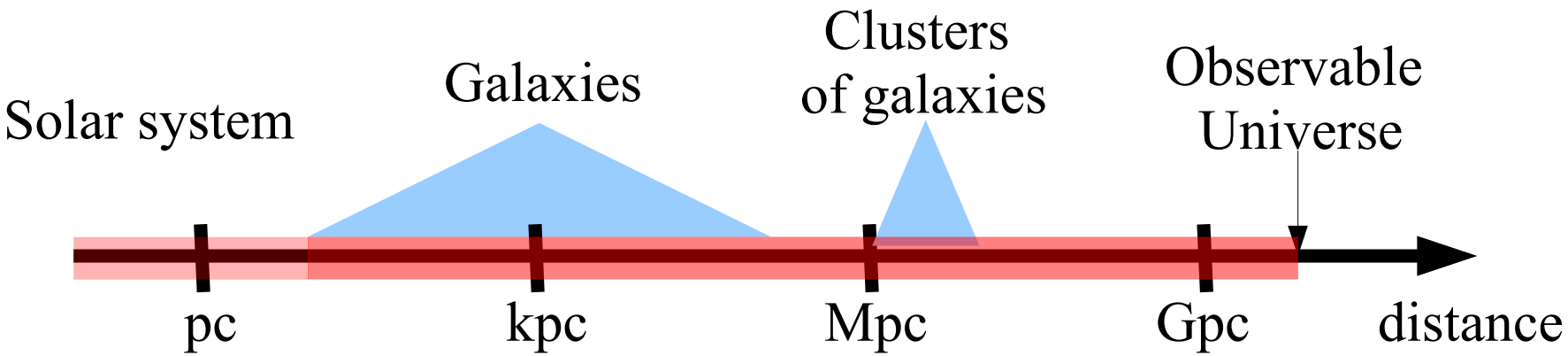


Assumption,
but well motivated

Three different methods

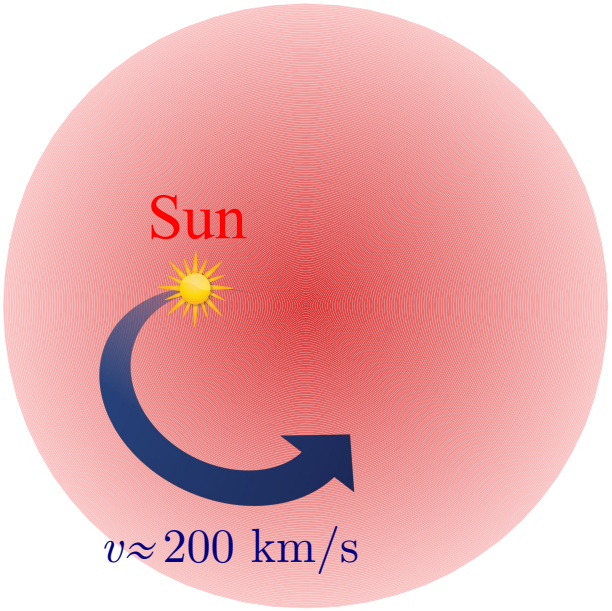
have been proposed

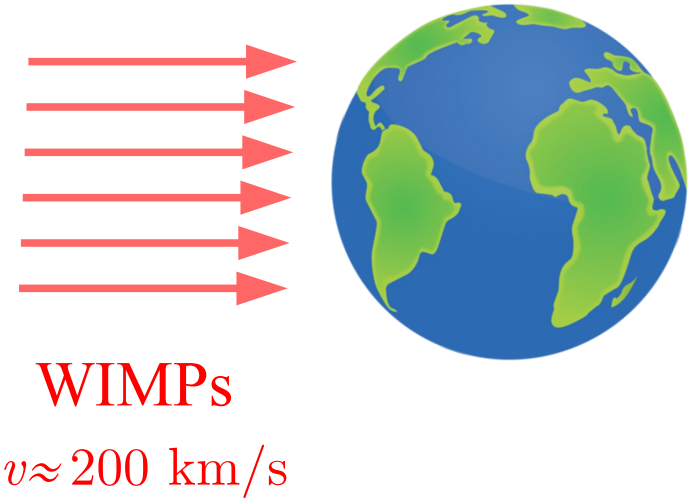
to probe WIMP dark matter

inside the Solar System

Direct dark matter searches

The Sun (and the Earth) is moving through a "gas" of dark matter particles. Or, from our point of view, there is a flux of dark matter particles going through the Earth.





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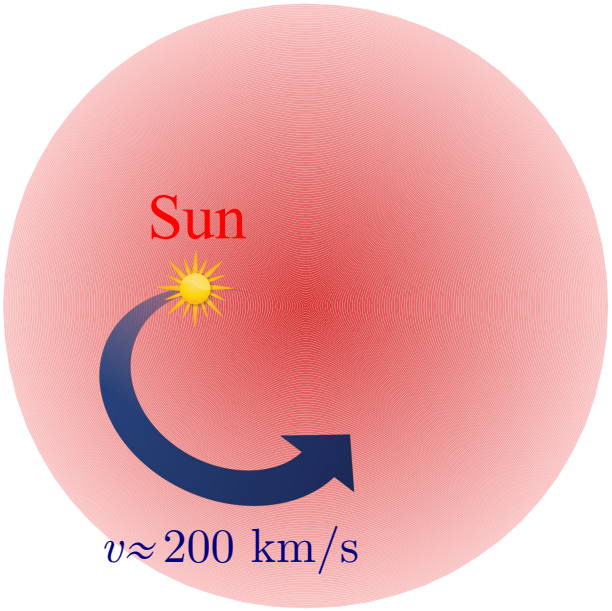
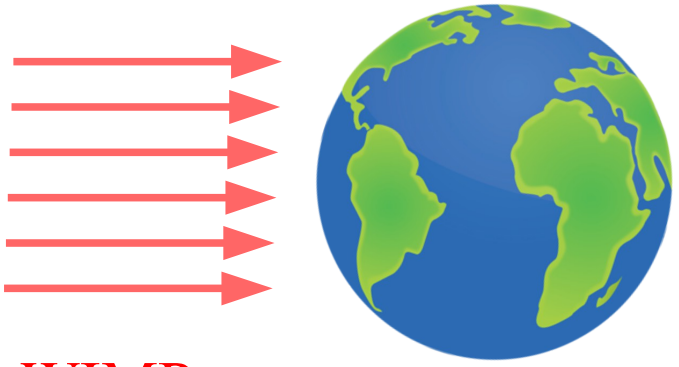
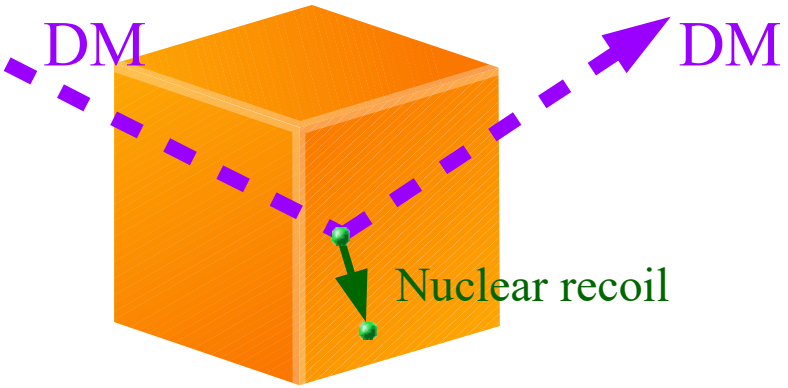




Once in a while a dark matter particle will interact with a nucleus. The nucleus then recoils, producing vibrations, ionizations or scintillation light in the detector.



Direct dark matter searches

Selected for a Viewpoint in *Physics*
PRL 118, 021303 (2017) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2017

Results from a Search for Dark Matter in the Complete LUX Exposure

D. S. Akerib,[1,2,3] S. Alsum,[4] H. M. Araújo,[5] X. Bai,[6] A. J. Bailey,[5] J. Balajthy,[7] P. Beltrame,[8] E. P. Bernard,[9,10] A. Bernstein,[11] T. P. Biesiadzinski,[1,2,3] E. M. Boulton,[9,10] R. Bramante,[1,2,3] P. Brás,[12] D. Byram,[13,14] S. B. Cahn,[10] M. C. Carmona-Benitez,[15] C. Chan,[16] A. A. Chiller,[13] C. Chiller,[13] A. Currie,[5] J. E. Cutter,[17] T. J. R. Davison,[8] A. Dobi,[18] J. E. Y. Dobson,[19] E. Druszkiewicz,[20] B. N. Edwards,[10] C. H. Faham,[18] S. Fiorucci,[16,18] R. J. Gaitskell,[16] V. M. Gehman,[18] C. Ghag,[19] K. R. Gibson,[1] M. G. D. Gilchriese,[18] C. R. Hall,[7] M. Hanhardt,[6,14] S. J. Haselschwardt,[15] S. A. Hertel,[9,10,*] D. P. Hogan,[9] M. Horn,[14,9,10] D. Q. Huang,[16] C. M. Ignarra,[2,3] M. Ihm,[9] R. G. Jacobsen,[9] W. Ji,[1,2,3] K. Kamdin,[9] K. Kazkaz,[11] D. Khaitan,[20] R. Knoche,[7] N. A. Larsen,[10] C. Lee,[1,2,3] B. G. Lenardo,[17,11] K. T. Lesko,[18] A. Lindote,[12] M. I. Lopes,[12] A. Manalaysay,[17,†] R. L. Mannino,[21] M. F. Marzioni,[8] D. N. McKinsey,[9,18,10] D.-M. Mei,[13] J. Mock,[22] M. Moongweluwan,[20] J. A. Morad,[17] A. St. J. Murphy,[8] C. Nehrkorn,[15] H. N. Nelson,[15] F. Neves,[12] K. O'Sullivan,[9,18,10] K. C. Oliver-Mallory,[9] K. J. Palladino,[4,2,3] E. K. Pease,[9,18,10] P. Phelps,[1] L. Reichhart,[19] C. Rhyne,[16] S. Shaw,[19] T. A. Shutt,[1,2,3] C. Silva,[12] M. Solmaz,[15] V. N. Solovov,[12] P. Sorensen,[18] S. Stephenson,[17] T. J. Sumner,[5] M. Szydagis,[22] D. J. Taylor,[14] W. C. Taylor,[16] B. P. Tennyson,[10] P. A. Terman,[21] D. R. Tiedt,[6] W. H. To,[1,2,3] M. Tripathi,[17] L. Tvrznikova,[9,10] S. Uvarov,[17] J. R. Verbus,[16] R. C. Webb,[21] J. T. White,[21] T. J. Whitis,[1,2,3] M. S. Witherell,[18] F. L. H. Wolfs,[20] J. Xu,[11] K. Yazdani,[5] S. K. Young,[22] and C. Zhang[13]

(LUX Collaboration)

Selected for a Viewpoint in *Physics*
PRL 119, 181301 (2017) PHYSICAL REVIEW LETTERS week ending 3 NOVEMBER 2017

First Dark Matter Search Results from the XENON1T Experiment

E. Aprile,[1] J. Aalbers,[2,*] F. Agostini,[3,4] M. Alfonsi,[5] F. D. Amaro,[6] M. Anthony,[1] F. Arneodo,[7] P. Barrow,[8] L. Baudis,[8] B. Bauermeister,[9] M. L. Benabderrahmane,[7] T. Berger,[10] P. A. Breur,[2] A. Brown,[2] A. Brown,[8] E. Brown,[10] S. Bruenner,[11] G. Bruno,[3] R. Budnik,[12] L. Bütikofer,[13,†] J. Calvén,[9] J. M. R. Cardoso,[6] M. Cervantes,[14] D. Cichon,[11] D. Coderre,[13] A. P. Colijn,[2] J. Conrad,[9] J. P. Cussonneau,[15] M. P. Decowski,[2] P. de Perio,[1] P. Di Gangi,[4] A. Di Giovanni,[7] S. Diglio,[15] G. Eurin,[11] J. Fei,[16] A. D. Ferella,[9] A. Fieguth,[17] W. Fulgione,[3,18] A. Gallo Rosso,[3] M. Galloway,[8] F. Gao,[1] M. Garbini,[4] R. Gardner,[19] C. Geis,[5] L. W. Goetzke,[1] L. Grandi,[19] Z. Greene,[1] C. Grignon,[5] C. Hasterok,[11] E. Hogenbirk,[2] J. Howlett,[1] R. Itay,[12] B. Kaminsky,[13,†] S. Kazama,[8] G. Kessler,[8] A. Kish,[8] H. Landsman,[12] R. F. Lang,[14] D. Lellouch,[12] L. Levinson,[12] Q. Lin,[1] S. Lindemann,[11,13] M. Lindner,[11] F. Lombardi,[16] J. A. M. Lopes,[6,‡] A. Manfredini,[12] I. Maris,[7] T. Marrodán Undagoitia,[11] J. Masbou,[15] F. V. Massoli,[4] D. Masson,[14] D. Mayani,[8] M. Messina,[1] K. Micheneau,[15] A. Molinario,[3] K. Morå,[9] M. Murra,[17] J. Naganoma,[20] K. Ni,[16] U. Oberlack,[5] P. Pakarha,[8] B. Pelssers,[9] R. Persiani,[15] F. Piastra,[8] J. Pienaar,[14] V. Pizzella,[11] M.-C. Piro,[10] G. Plante,[1,§] N. Priel,[12] L. Rauch,[11] S. Reichard,[8,14] C. Reuter,[14] B. Riedel,[19] A. Rizzo,[1] S. Rosendahl,[17] N. Rupp,[11] R. Saldanha,[19] J. M. F. dos Santos,[6] G. Sartorelli,[4] M. Scheibelhut,[5] S. Schindler,[5] J. Schreiner,[11] M. Schumann,[13] L. Scotto Lavina,[21] M. Selvi,[4] P. Shagin,[20] E. Shockley,[19] M. Silva,[6] H. Simgen,[11] M. v. Sivers,[13,†] A. Stein,[22] S. Thapa,[19] D. Thers,[15] A. Tiseni,[2] G. Trinchero,[18] C. Tunnell,[19,‖] M. Vargas,[17] N. Upole,[19] H. Wang,[22] Z. Wang,[3] Y. Wei,[8] C. Weinheimer,[17] J. Wulf,[8] J. Ye,[16] Y. Zhang,[1] and T. Zhu[1]

(XENON Collaboration)[¶]

Selected for a Viewpoint in *Physics*
PRL 119, 181302 (2017) PHYSICAL REVIEW LETTERS week ending 3 NOVEMBER 2017

Dark Matter Results from 54-Ton-Day Exposure of PandaX-II Experiment

Xiangyi Cui,[1] Abdusalam Abdukerim,[2] Wei Chen,[1] Xun Chen,[1] Yunhua Chen,[3] Binbin Dong,[1] Deqing Fang,[4] Changbo Fu,[1] Karl Giboni,[1] Franco Giuliani,[1] Linhui Gu,[1] Yikun Gu,[1] Xuyuan Guo,[3] Zhifan Guo,[5] Ke Han,[1] Changda He,[1] Di Huang,[1] Shengming He,[3] Xingtao Huang,[6] Zhou Huang,[1] Xiangdong Ji,[7,1,§] Yonglin Ju,[5] Shaoli Li,[1] Yao Li,[1] Heng Lin,[1] Huaxuan Liu,[5] Jianglai Liu,[4,7,*] Yugang Ma,[4] Yajun Mao,[8] Kaixiang Ni,[1] Jinhua Ning,[3] Xiangxiang Ren,[1] Fang Shi,[1] Andi Tan,[9,†] Cheng Wang,[5] Hongwei Wang,[4] Meng Wang,[6] Qiuhong Wang,[4,‡] Siguang Wang,[8] Xiuli Wang,[5] Xuming Wang,[1] Qinyu Wu,[1] Shiyong Wu,[3] Mengjiao Xiao,[9,10] Pengwei Xie,[1] Binbin Yan,[6] Yong Yang,[1] Jianfeng Yue,[3] Dan Zhang,[1] Hongguang Zhang,[1] Tao Zhang,[1] Tianqi Zhang,[1] Li Zhao,[1] Jifang Zhou,[3] Ning Zhou,[1] and Xiaopeng Zhou[8]

(PandaX-II Collaboration)

PRL 118, 251301 (2017) PHYSICAL REVIEW LETTERS week ending 23 JUNE 2017

Dark Matter Search Results from the PICO-60 C_3F_8 Bubble Chamber

C. Amole,[1] M. Ardid,[2] I. J. Arnquist,[3] D. M. Asner,[3] D. Baxter,[4,5,*] E. Behnke,[6] P. Bhattacharjee,[7] H. Borsodi,[6] M. Bou-Cabo,[2] P. Campion,[8] G. Cao,[1] C. J. Chen,[4] U. Chowdhury,[1] K. Clark,[9,10] J. I. Collar,[11] P. S. Cooper,[5] M. Crisler,[5,3] G. Crowder,[1] C. E. Dahl,[4,5] M. Das,[7] S. Fallows,[12] J. Farine,[9] I. Felis,[2] R. Filgas,[13] F. Girard,[9,14] G. Giroux,[1,§] J. Hall,[3] O. Harris,[6,15] E. W. Hoppe,[3] M. Jin,[4] C. B. Krauss,[12] M. Laurin,[14] I. Lawson,[9,10] A. Leblanc,[9] I. Levine,[6] W. H. Lippincott,[5] F. Mamedov,[13] D. Maurya,[16] P. Mitra,[12] T. Nania,[6] R. Neilson,[8] A. J. Noble,[1] S. Olson,[1] A. Ortega,[11] A. Plante,[14] R. Podviyanuk,[9] S. Priya,[16] A. E. Robinson,[5] A. Roeder,[6] R. Rucinski,[5] O. Scallon,[9] S. Seth,[7] A. Sonnenschein,[5] N. Starinski,[14] I. Štekl,[13] F. Tardif,[14] E. Vázquez-Jáuregui,[17,9] J. Wells,[6] U. Wichoski,[9] Y. Yan,[16] V. Zacek,[14] and J. Zhang[4]

(PICO Collaboration)

PRL 116, 071301 (2016) PHYSICAL REVIEW LETTERS week ending 19 FEBRUARY 2016

New Results from the Search for Low-Mass Weakly Interacting Massive Particles with the CDMS Low Ionization Threshold Experiment

R. Agnese,[22] A. J. Anderson,[3] T. Aramaki,[10] M. Asai,[10] W. Baker,[15] D. Balakishiyeva,[22] D. Barker,[24] R. Basu Thakur,[3,23] D. A. Bauer,[3] J. Billard,[5] A. Borgland,[10] M. A. Bowles,[14] P. L. Brink,[10] R. Bunker,[11] B. Cabrera,[13] D. O. Caldwell,[19] R. Calkins,[12] D. G. Cerdeno,[2] H. Chagani,[24] Y. Chen,[14] J. Cooley,[12] B. Cornell,[1] P. Cushman,[24] M. Daal,[18] P. C. F. Di Stefano,[8] T. Doughty,[18] L. Esteban,[16] S. Fallows,[24] E. Figueroa-Feliciano,[6] M. Ghaith,[8] G. L. Godfrey,[10] S. R. Golwala,[1] J. Hall,[7] H. R. Harris,[15] T. Hofer,[24] D. Holmgren,[3] L. Hsu,[3] M. E. Huber,[20] D. Jardin,[12] A. Jastram,[15] O. Kamaev,[8] B. Kara,[12] M. H. Kelsey,[10] A. Kennedy,[24] A. Leder,[5] B. Loer,[3] E. Lopez Asamar,[16] P. Lukens,[3] R. Mahapatra,[15] V. Mandic,[24] N. Mast,[24] N. Mirabolfathi,[18] R. A. Moffatt,[13] J. D. Morales Mendoza,[15] S. M. Oser,[17] K. Page,[8] W. A. Page,[17] R. Partridge,[10] M. Pepin,[24,*] A. Phipps,[18] K. Prasad,[15] M. Pyle,[18] H. Qiu,[12] W. Rau,[8] P. Redl,[13] A. Reisetter,[21] Y. Ricci,[8] A. Roberts,[25] H. E. Rogers,[24] T. Saab,[22] B. Sadoulet,[18,4] J. Sander,[25] K. Schneck,[10] R. W. Schnee,[11] S. Scorza,[12] B. Serfass,[18] B. Shank,[13] D. Speller,[18] D. Toback,[15] R. Underwood,[8] S. Upadhyayula,[15] A. N. Villano,[24] B. Welliver,[22] J. S. Wilson,[15] D. H. Wright,[10] S. Yellin,[13] J. J. Yen,[13] B. A. Young,[9] and J. Zhang[24]

(SuperCDMS Collaboration)

Direct dark matter searches

Selected for a Viewpoint in *Physics*
PRL 118, 021303 (2017) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2017

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(LUX Collaboration)

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PRL 119, 181301 (2017) PHYSICAL REVIEW LETTERS week ending 3 NOVEMBER 2017

First Dark Matter Search Results from the XENON1T Experiment

E. Aprile,[1] J. Aalbers,[2,*] F. Agostini,[3,4] M. Alfonsi,[5] F. D. Amaro,[6] M. Anthony,[1] F. Arneodo,[7] P. Barrow,[8] L. Baudis,[8] B. Bauermeister,[9] M. L. Benabderrahmane,[7] T. Berger,[10] P. A. Breur,[2] A. Brown,[2] A. Brown,[8] E. Brown,[10] S. Bruenner,[11] G. Bruno,[3] R. Budnik,[12] L. Bütikofer,[13,†] J. Calvén,[9] J. M. R. Cardoso,[6] M. Cervantes,[14] D. Cichon,[11] D. Coderre,[13] A. P. Colijn,[2] J. Conrad,[9] J. P. Cussonneau,[15] M. P. [illegible]ski,[2] P. de Perio,[1] P. Di Gangi,[4] A. Di Giovanni,[7] S. Diglio,[15] G. Eurin,[11] J. Fei,[16] A. D. Ferella,[9] A. Fieguth,[17] [illegible],[3,18] A. Gallo Rosso,[3] M. Galloway,[8] F. Gao,[1] M. Garbini,[4] R. Gardner,[19] C. Geis,[5] L. W. Goetzke,[1] L. G[illegible],[1] C. Grignon,[5] C. Hasterok,[11] E. Hogenbirk,[2] J. Howlett,[1] R. Itay,[12] B. Kaminsky,[13,†] S. Kazama,[8] G[illegible] Landsman,[12] R. F. Lang,[14] D. Lellouch,[12] L. Levinson,[12] Q. Lin,[1] S. Lindemann,[11,13] M. I[illegible] Lopes,[6,‡] A. Manfredini,[12] I. Maris,[7] T. Marrodán Undagoitia,[11] J. Masbou,[15] F[illegible],[8] M. Messina,[1] K. Micheneau,[15] A. Molinario,[3] K. Morå,[9] M. Murra,[17] J[illegible]varha,[8] B. Pelssers,[9] R. Persiani,[15] F. Piastra,[8] J. Pienaar,[14] V. Pizzel[illegible],[11] S. Reichard,[8,14] C. Reuter,[14] B. Riedel,[19] A. Rizzo,[1] S. Rose[illegible] Sartorelli,[4] M. Scheibelhut,[5] S. Schindler,[5] J. Schreiner[illegible] E. Shockley,[19] M. Silva,[6] H. Simgen,[11] M. v. Sive[illegible] Tunnell,[19,‖] M. Vargas,[17] N. Upole,[19] [illegible] Y. Zhang,[1] and T. Zhu[1]

Selected for a Viewpoint in *Physics*
PRL 119, 181302 (2017) PHYSICAL REVIEW LETTERS week ending 3 NOVEMBER 2017

Dark Matter Results from 54-Ton-Day Exposure of PandaX-II Experiment

Xiangyi Cui,[1] Abdusalam Abdukerim,[2] Wei Chen,[1] Xun Chen,[1] Yunhua Chen,[3] Binbin Dong,[1] Deqing F[illegible] Changbo Fu,[1] Karl Giboni,[1] Franco Giuliani,[1] Linhui Gu,[1] Yikun Gu,[1] Xuyuan Guo,[3] Zhifan Guo,[5] Ke Han,[1] [illegible] Di Huang,[1] Shengming He,[3] Xingtao Huang,[6] Zhou Huang,[1] Xiangdong Ji,[7,1,§] Yonglin Ju,[5] Shaoli Li,[1] Y[illegible] Huaxuan Liu,[5] Jianglai Liu,[4,7,*] Yugang Ma,[4] Yajun Mao,[8] Kaixiang Ni,[1] Jinhua Ning,[3] Xiangxi[illegible] Andi Tan,[9,†] Cheng Wang,[5] Hongwei Wang,[4] Meng Wang,[6] Qiuhong Wang,[4,‡] Siguang [illegible] Xuming Wang,[1] Qinyu Wu,[1] Shiyong Wu,[3] Mengjiao Xiao,[9,10] Pengwei Xie,[1] Binbin Ya[illegible] Dan Zhang,[1] Hongguang Zhang,[1] Tao Zhang,[1] Tianqi Zhang,[1] Li Zhao,[1] Jifang Zhou[3]

(PandaX-II Collaboration)

PHYSICAL REVIEW LETTERS week ending 23 JUNE 2017

[illegible]n Results from the PICO-60 C_3F_8 Bubble Chamber

[illegible] Amquist,[3] D. M. Asner,[3] D. Baxter,[4,5,*] E. Behnke,[6] P. Bhattacharjee,[7] H. Borsodi,[6] [illegible] G. Cao,[1] C. J. Chen,[4] U. Chowdhury,[1] K. Clark,[9,10] J. I. Collar,[11] P. S. Cooper,[5] M. Crisler,[5,3] [illegible] M. Das,[7] S. Fallows,[12] J. Farine,[9] I. Felis,[2] R. Filgas,[13] F. Girard,[9,14] G. Giroux,[1,§] J. Hall,[3] [illegible] Hoppe,[3] M. Jin,[4] C. B. Krauss,[12] M. Laurin,[14] I. Lawson,[9,10] A. Leblanc,[9] I. Levine,[6] W. H. Lippincott,[5] [illegible] D. Maurya,[16] P. Mitra,[12] T. Nania,[6] R. Neilson,[8] A. J. Noble,[1] S. Olson,[1] A. Ortega,[11] A. Plante,[14] [illegible]viyanuk,[9] S. Priya,[16] A. E. Robinson,[5] A. Roeder,[6] R. Rucinski,[5] O. Scallon,[9] S. Seth,[7] A. Sonnenschein,[5] [illegible]inski,[14] I. Štekl,[13] F. Tardif,[14] E. Vázquez-Jáuregui,[17,9] J. Wells,[6] U. Wichoski,[9] Y. Yan,[16] V. Zacek,[14] and J. Zhang[4]

(PICO Collaboration)

PHYSICAL REVIEW LETTERS week ending 19 FEBRUARY 2016

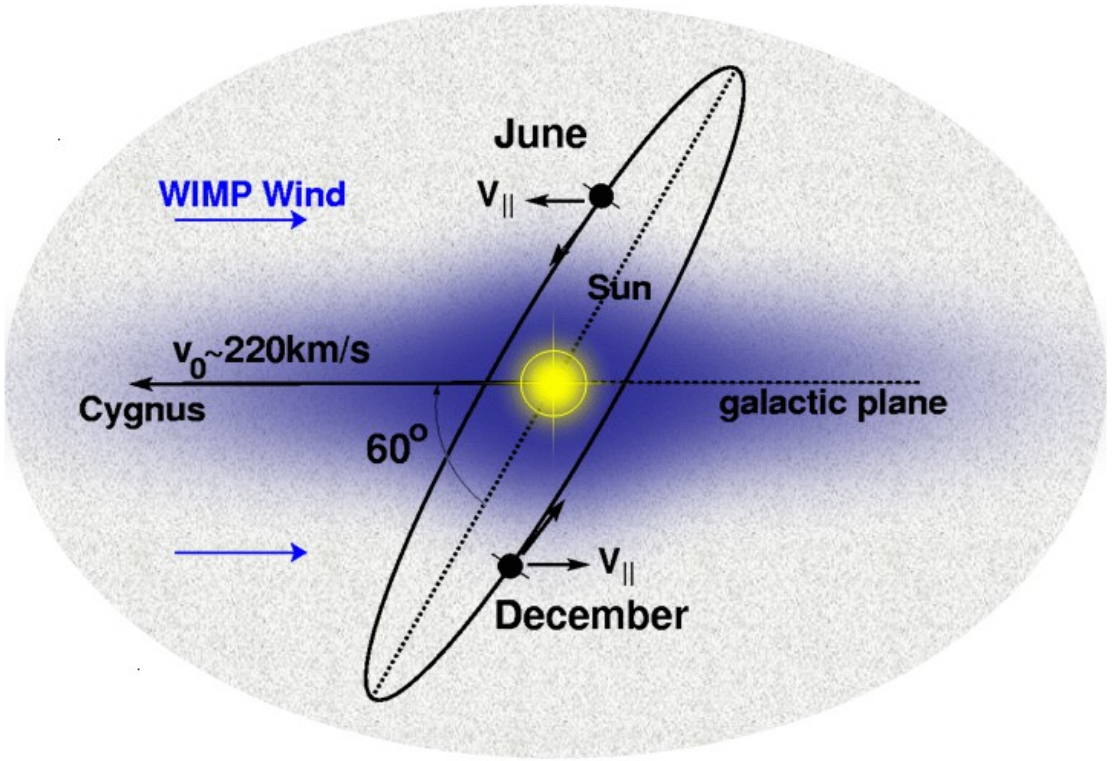
[illegible]om the Search for Low-Mass Weakly Interacting Massive Particles with the CDMS Low Ionization Threshold Experiment

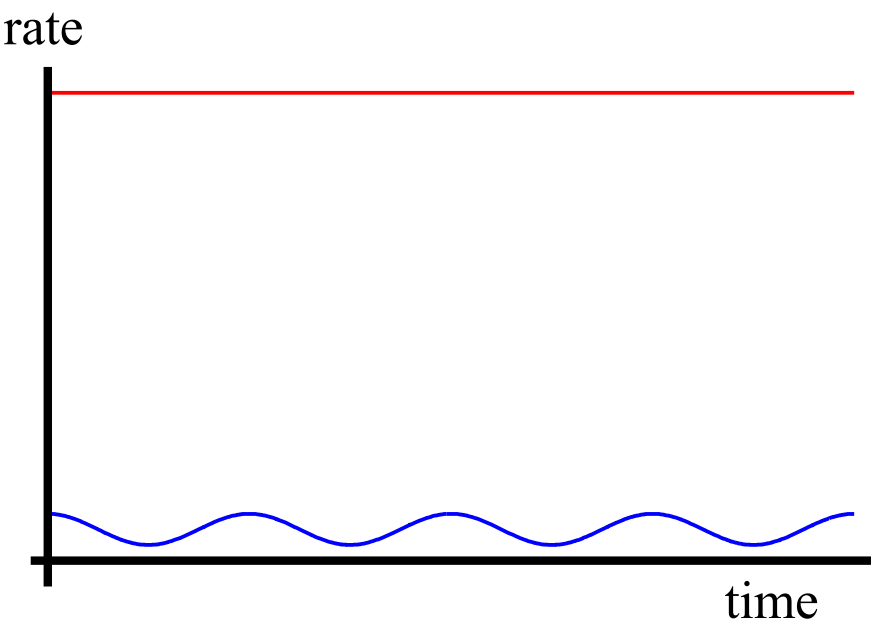
[illegible],[22] A. J. Anderson,[3] T. Aramaki,[10] M. Asai,[10] W. Baker,[15] D. Balakishiyeva,[22] D. Barker,[24] R. Basu Thakur,[3,23] [illegible]A. Bauer,[3] J. Billard,[5] A. Borgland,[10] M. A. Bowles,[14] P. L. Brink,[10] R. Bunker,[11] B. Cabrera,[13] D. O. Caldwell,[19] R. Calkins,[12] D. G. Cerdeno,[2] H. Chagani,[24] Y. Chen,[14] J. Cooley,[12] B. Cornell,[1] P. Cushman,[24] M. Daal,[18] P. C. F. Di Stefano,[8] T. Doughty,[18] L. Esteban,[16] S. Fallows,[24] E. Figueroa-Feliciano,[6] M. Ghaith,[8] G. L. Godfrey,[10] S. R. Golwala,[1] J. Hall,[7] H. R. Harris,[15] T. Hofer,[24] D. Holmgren,[3] L. Hsu,[3] M. E. Huber,[20] D. Jardin,[12] A. Jastram,[15] O. Kamaev,[8] B. Kara,[12] M. H. Kelsey,[10] A. Kennedy,[24] A. Leder,[5] B. Loer,[3] E. Lopez Asamar,[16] P. Lukens,[3] R. Mahapatra,[15] V. Mandic,[24] N. Mast,[24] N. Mirabolfathi,[18] R. A. Moffatt,[13] J. D. Morales Mendoza,[15] S. M. Oser,[17] K. Page,[8] W. A. Page,[17] R. Partridge,[10] M. Pepin,[24,*] A. Phipps,[18] K. Prasad,[15] M. Pyle,[18] H. Qiu,[12] W. Rau,[8] P. Redl,[13] A. Reisetter,[21] Y. Ricci,[8] A. Roberts,[25] H. E. Rogers,[24] T. Saab,[22] B. Sadoulet,[18,4] J. Sander,[25] K. Schneck,[10] R. W. Schnee,[11] S. Scorza,[12] B. Serfass,[18] B. Shank,[13] D. Speller,[18] D. Toback,[15] R. Underwood,[8] S. Upadhyayula,[15] A. N. Villano,[24] B. Welliver,[22] J. S. Wilson,[15] D. H. Wright,[10] S. Yellin,[13] J. J. Yen,[13] B. A. Young,[9] and J. Zhang[24]

(SuperCDMS Collaboration)

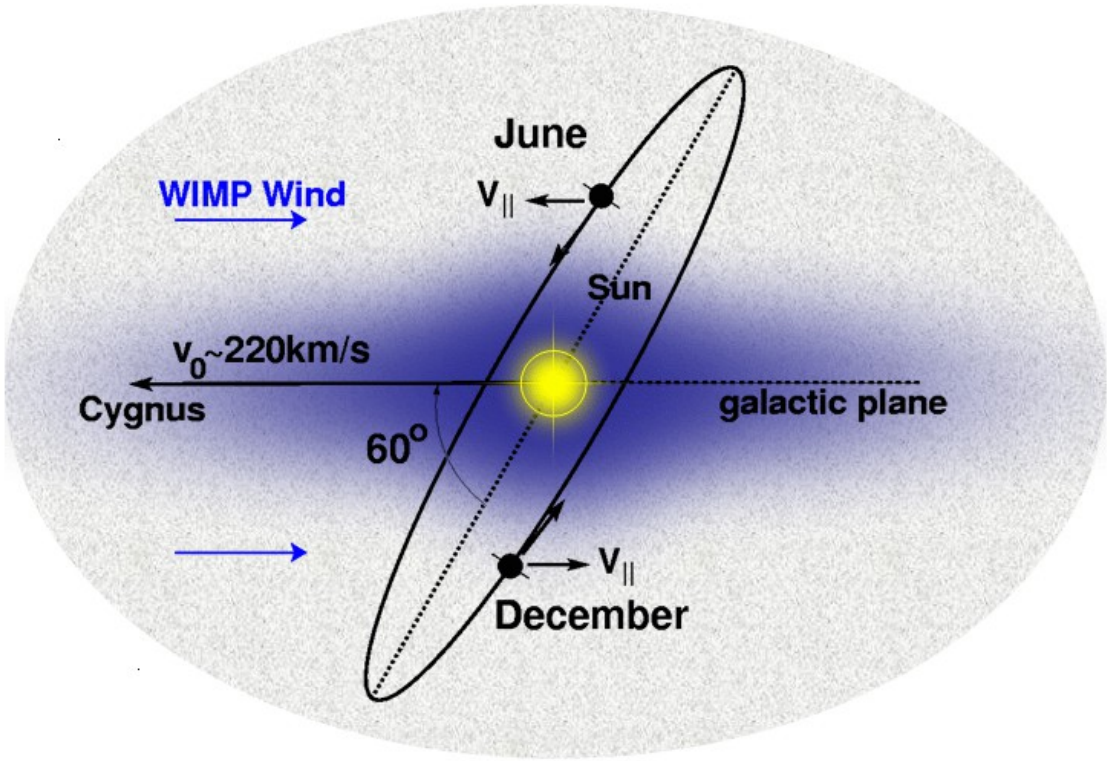
no evidence for DM-induced nuclear recoils

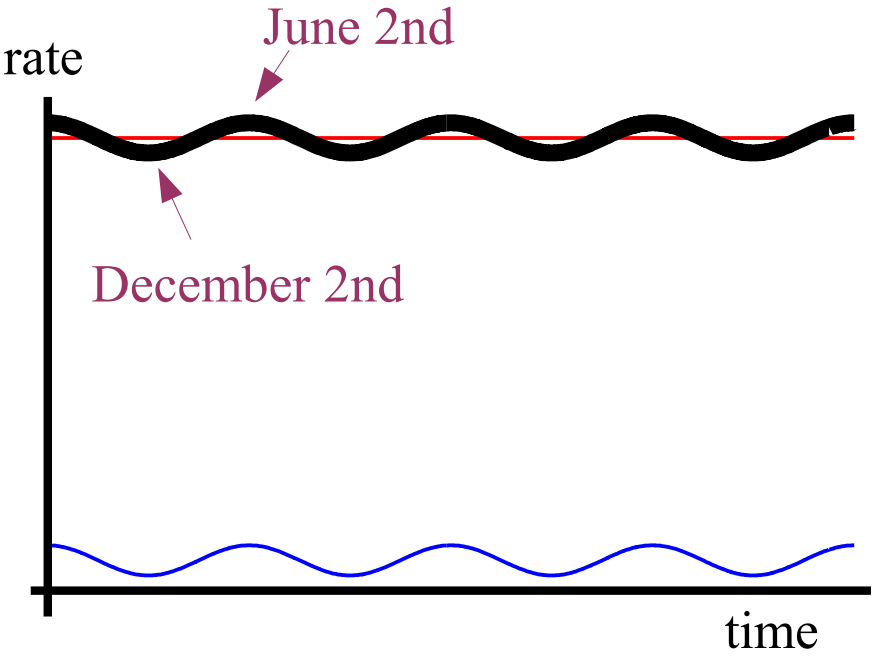
Annual modulation



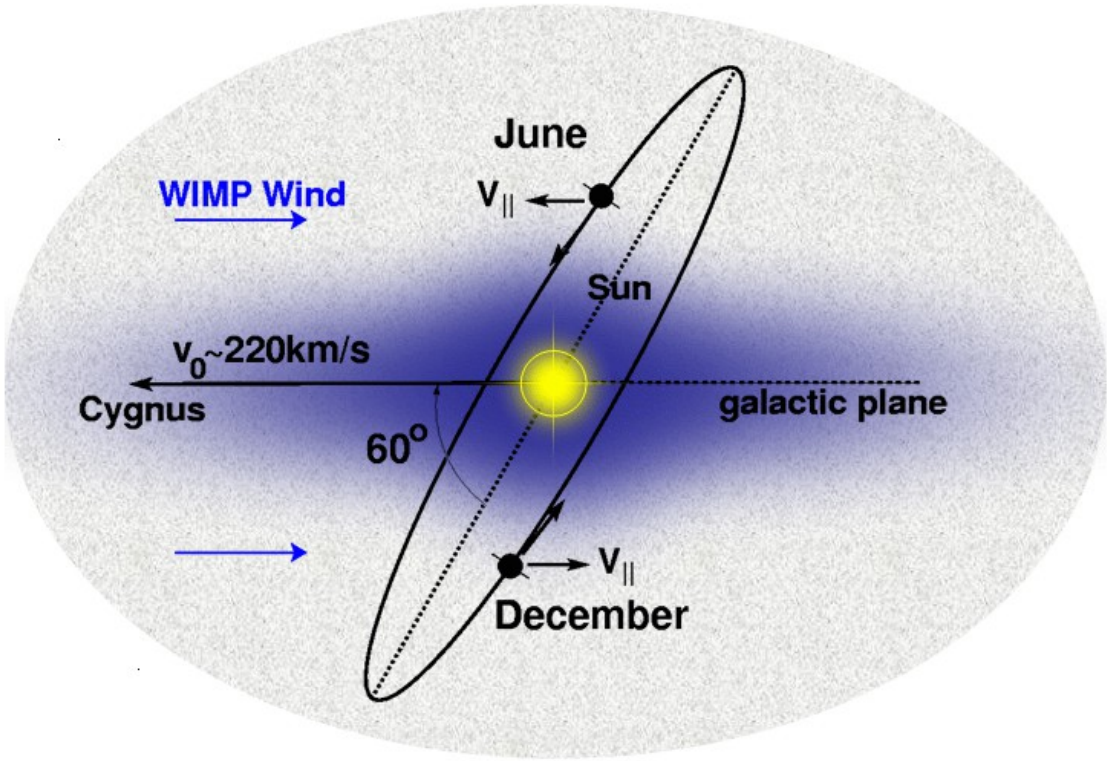


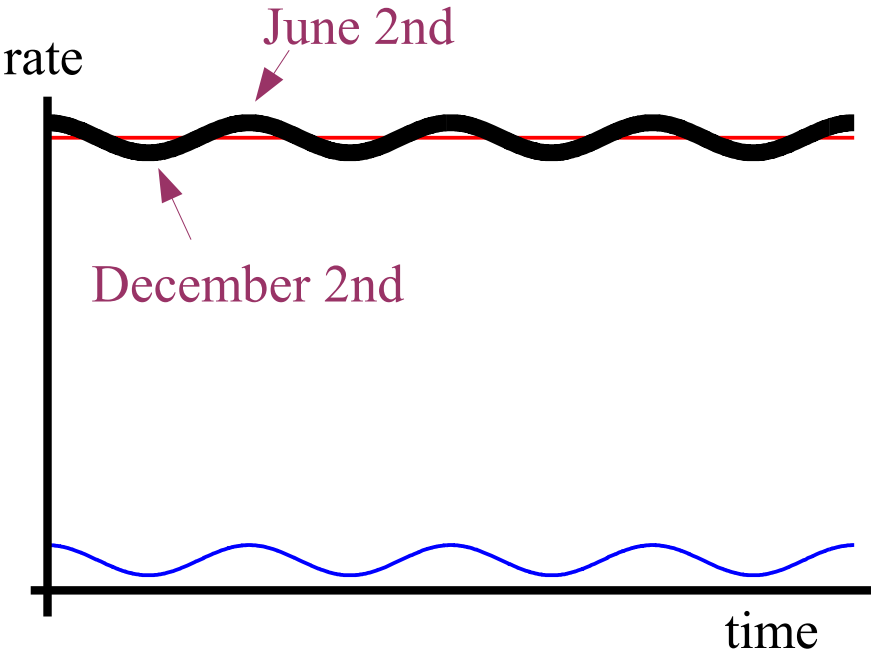
Annual modulation





Annual modulation

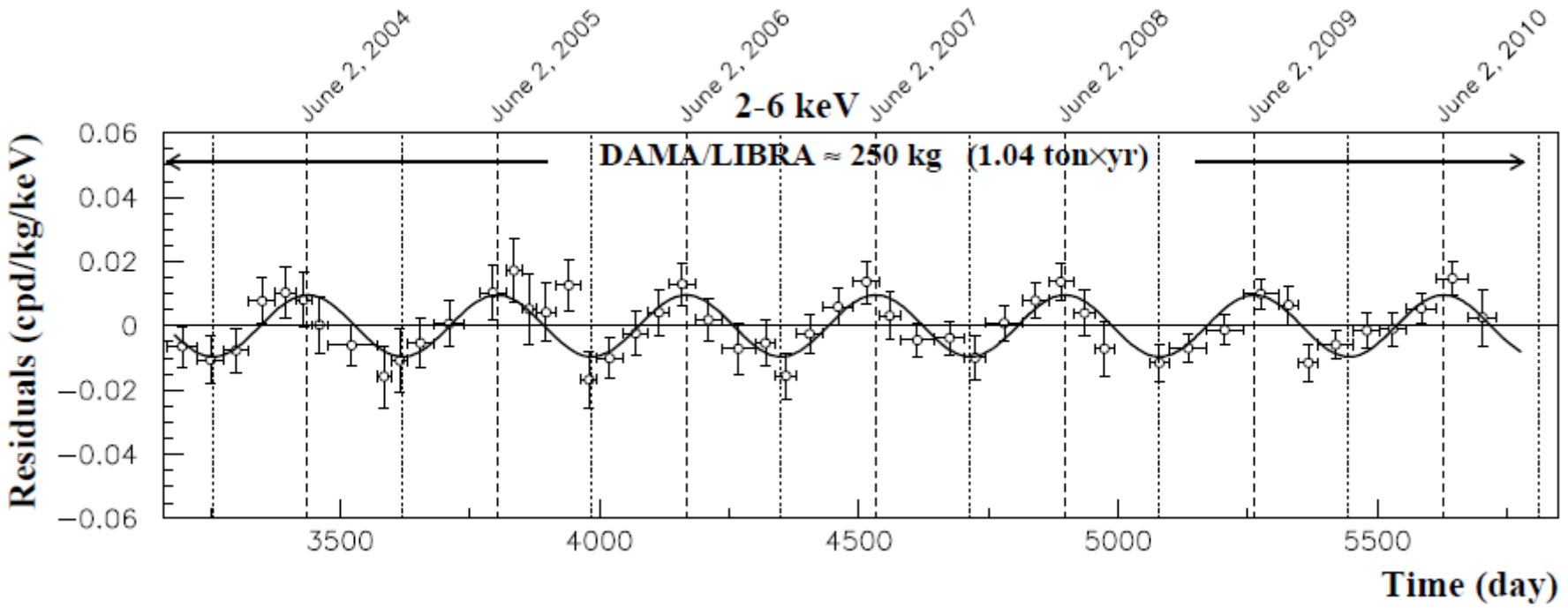




Modulation signal

$$S_{[E_-,E_+]} = \frac{1}{2}\frac{1}{E_+ - E_-}\left(R_{[E_-,E_+]}\Big|_{\text{June 1st}} - R_{[E_-,E_+]}\Big|_{\text{Dec 1st}}\right)$$

Annual modulation: the DAMA/LIBRA experiment



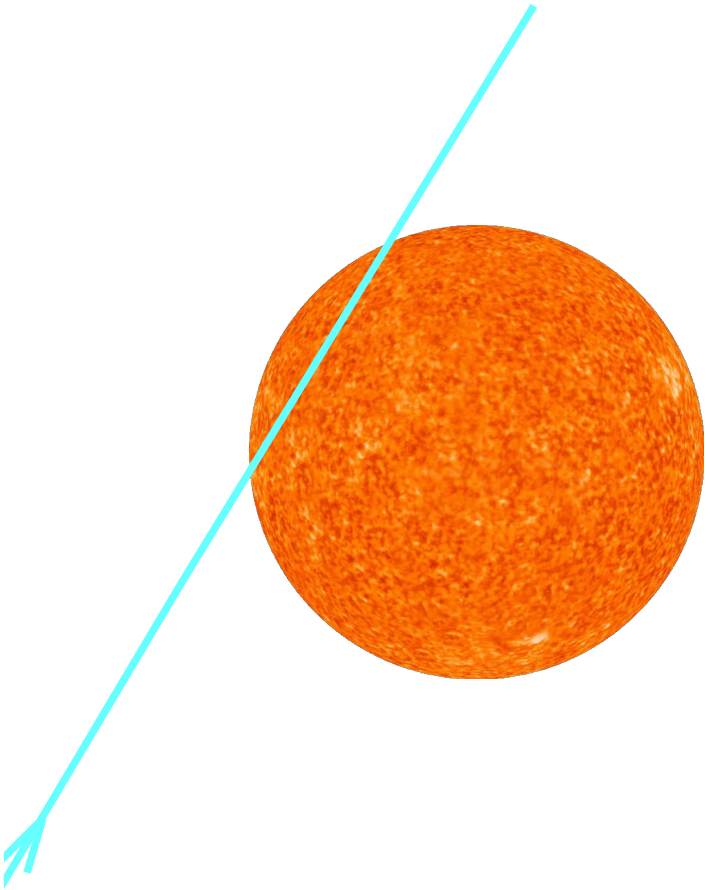
Modulation observed over 14 annual cycles, with a combined significance of 9.3σ.

$$S^{(\mathrm{DAMA})}_{[2.0,2.5]} = (1.75 \pm 0.37) \times 10^{-2}\ \mathrm{day}^{-1}\,\mathrm{kg}^{-1}\,\mathrm{keV}^{-1}$$

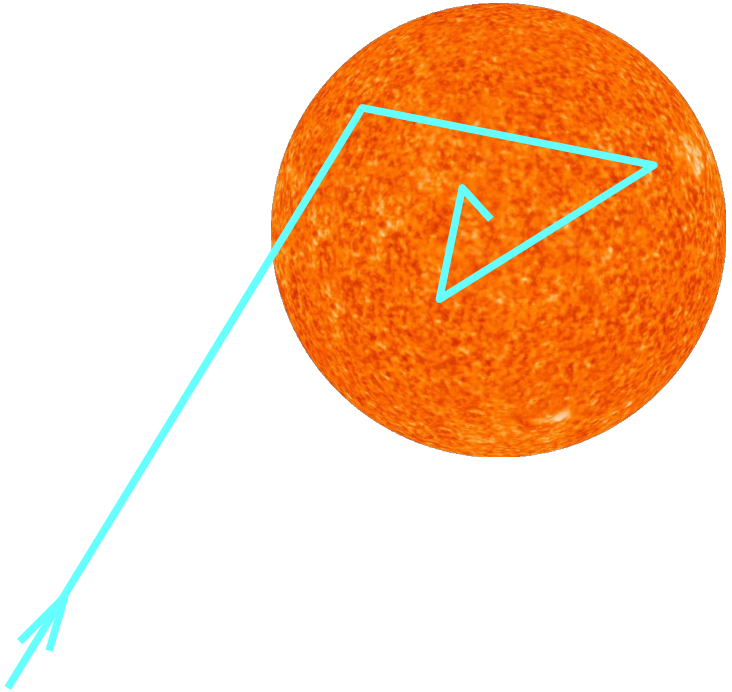
$$S^{(\mathrm{DAMA})}_{[2.5,3.0]} = (2.51 \pm 0.40) \times 10^{-2}\ \mathrm{day}^{-1}\,\mathrm{kg}^{-1}\,\mathrm{keV}^{-1}$$

$$S^{(\mathrm{DAMA})}_{[3.0,3.5]} = (2.16 \pm 0.40) \times 10^{-2}\ \mathrm{day}^{-1}\,\mathrm{kg}^{-1}\,\mathrm{keV}^{-1}$$

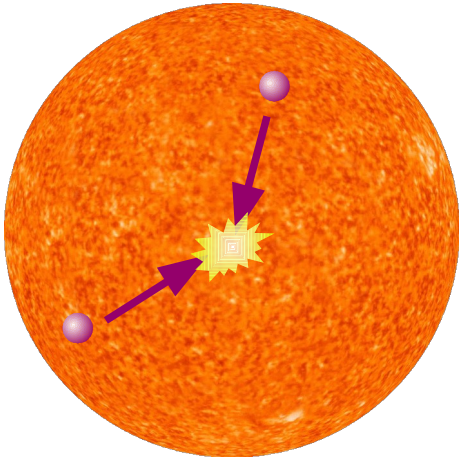
Neutrinos from annihilations in the Sun



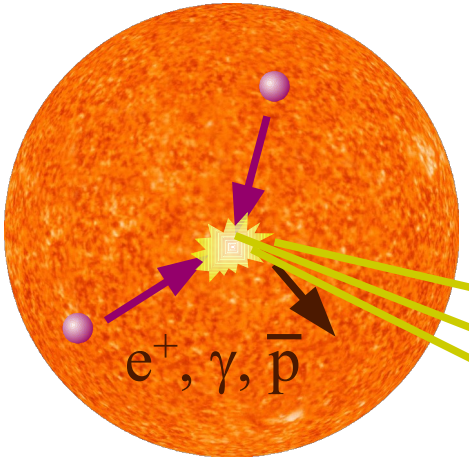
Neutrinos from annihilations in the Sun



Neutrinos from annihilations in the Sun



Neutrinos from annihilations in the Sun



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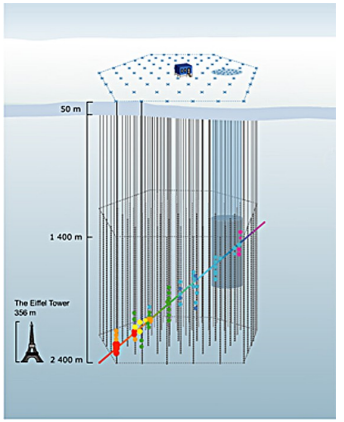
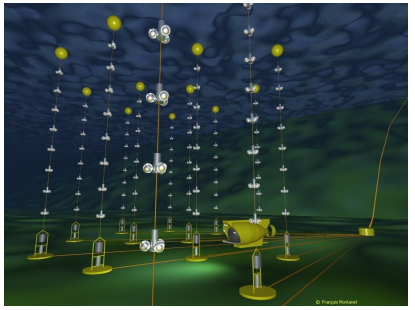
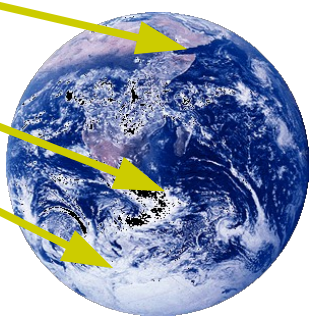
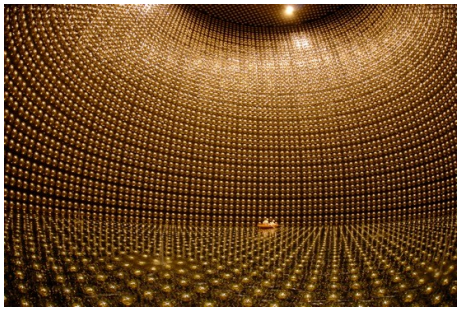


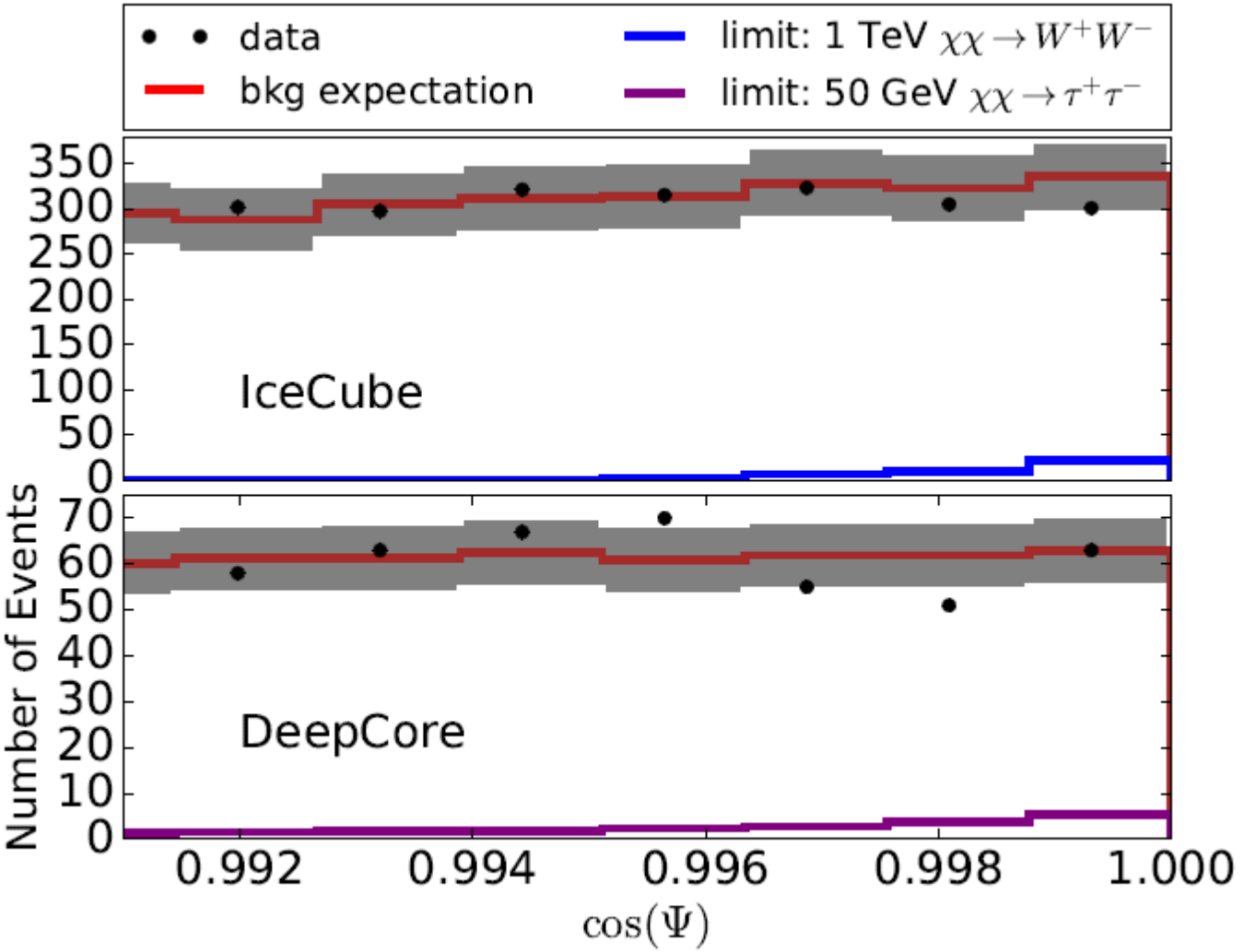






Neutrinos from annihilations in the Sun

Observations consistent with the background-only hypothesis



IceCube collaboration
ArXiv:1612.05949

Theoretical interpretation of the experimental results

Theoretical interpretation of the experimental results

- Rate of DM-induced scatterings

$$\frac{dR}{dE_R} = \frac{\rho_{\rm loc}}{m_A m_{\rm DM}} \int_{v \geq v_{\rm min}(E_R)} {\rm d}^3 v \, v f(\vec{v} + \vec{v}_{\rm obs}(t)) \frac{{\rm d}\sigma}{{\rm d}E_R}$$

- The neutrino flux from annihilations inside the Sun is, under plausible assumptions, determined by the capture rate inside the Sun:

$$C = \int_0^{R_\odot} 4\pi r^2 {\rm d}r \, \frac{\rho_{\rm loc}}{m_{\rm DM}} \int_{v \leq v_{\rm max}^{\rm (Sun)}(r)} {\rm d}^3 v \, \frac{f(\vec{v})}{v} \left(v^2 + [v_{\rm esc}(r)]^2\right) \times \int_{m_{\rm DM} v^2/2}^{2\mu_A^2 \left(v^2 + [v_{\rm esc}(r)]^2\right)/m_A} {\rm d}E_R \, \frac{{\rm d}\sigma}{{\rm d}E_R}$$

Theoretical interpretation of the experimental results

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Uncertainties from particle/nuclear physics and from astrophysics

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Theoretical interpretation of the experimental results

Uncertainties from particle/nuclear physics.

- Dark matter mass?

  For thermally produced dark matter, $m_{\rm DM}$ = few MeV – 100 TeV

- Differential cross section?

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_R} = \frac{m_A}{2\mu_A^2 v^2}\left(\sigma_{\rm SI} F_{\rm SI}^2(E_R) + \sigma_{\rm SD} F_{\rm SD}^2(E_R)\right)$$

Spin-independent and
spin-dependent cross sections
at zero momentum transfer

Nuclear form factors

(In some DM frameworks, other operators may also arise)

Theoretical interpretation of the experimental results

Uncertainties from astrophysics

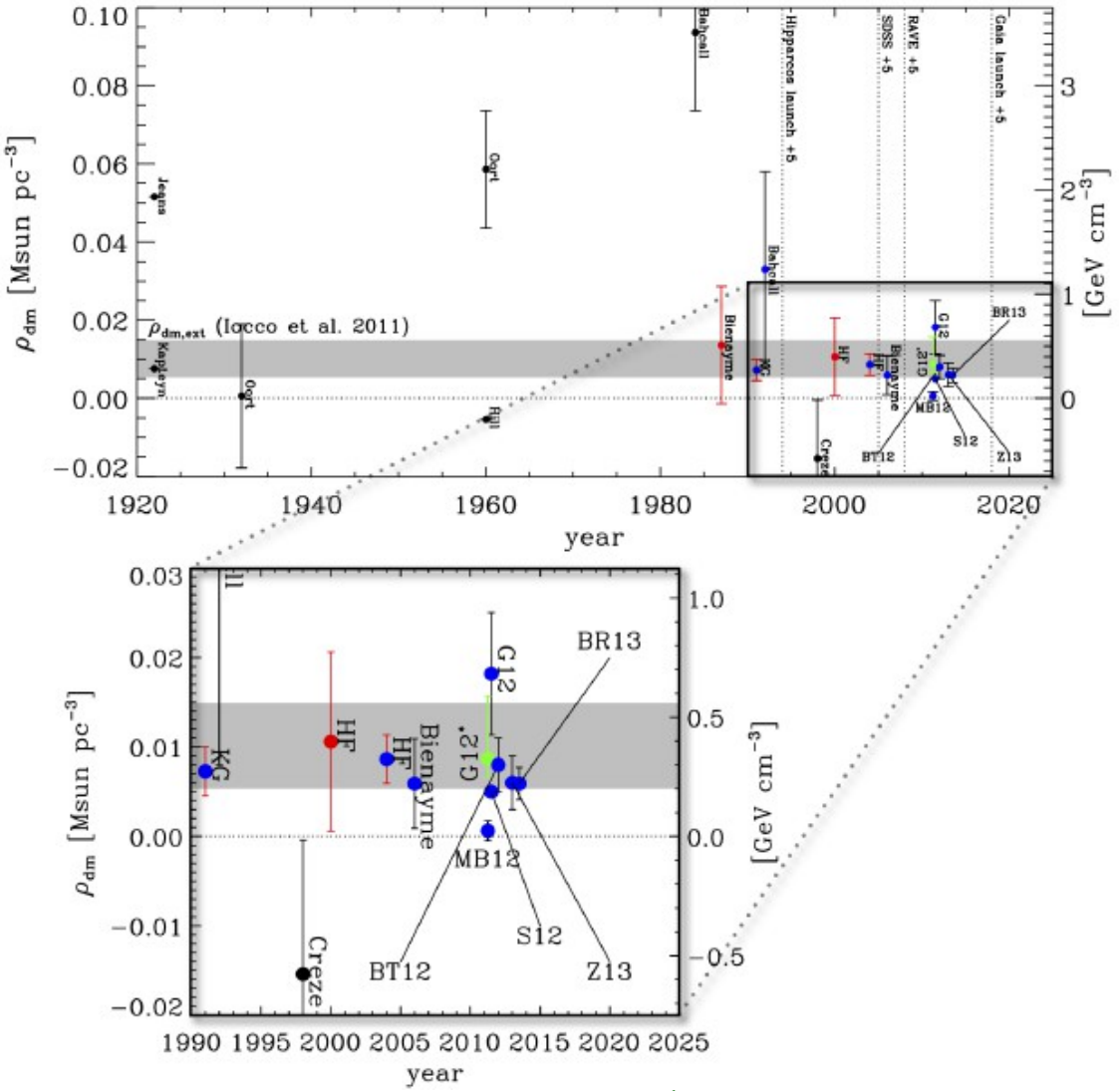
- Local dark matter density?

- "local measurements":

  From vertical kinematics of stars near (~1 kpc) the Sun

- "global measurements":

  From extrapolations of $\rho(r)$ determined from rotation curves at large r, to the position of the Solar System.



Theoretical interpretation of the experimental results

Uncertainties from astrophysics

- Local dark matter velocity distribution?

  Completely unknown. Rely on theoretical considerations

  - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.

$$\rho(r) \sim \frac{1}{r^2} \longrightarrow f(v) \sim \exp(-v^2/v_0^2)$$

Theoretical interpretation of the experimental results

Uncertainties from astrophysics

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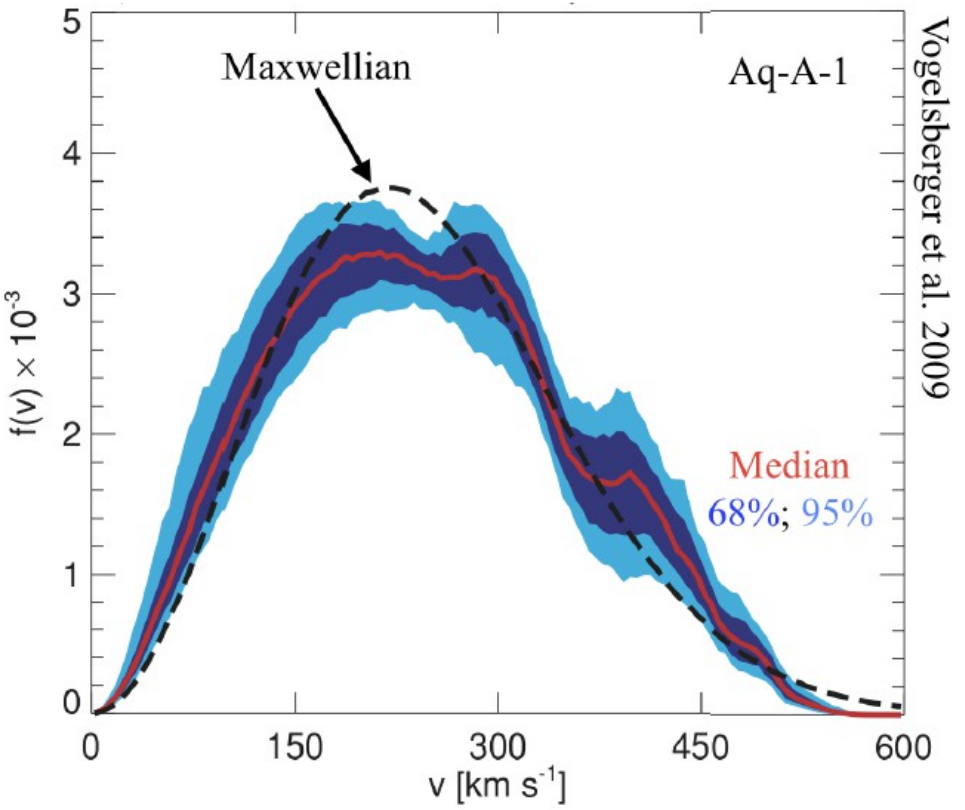
  - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann



Theoretical interpretation of the experimental results

Uncertainties from astrophysics

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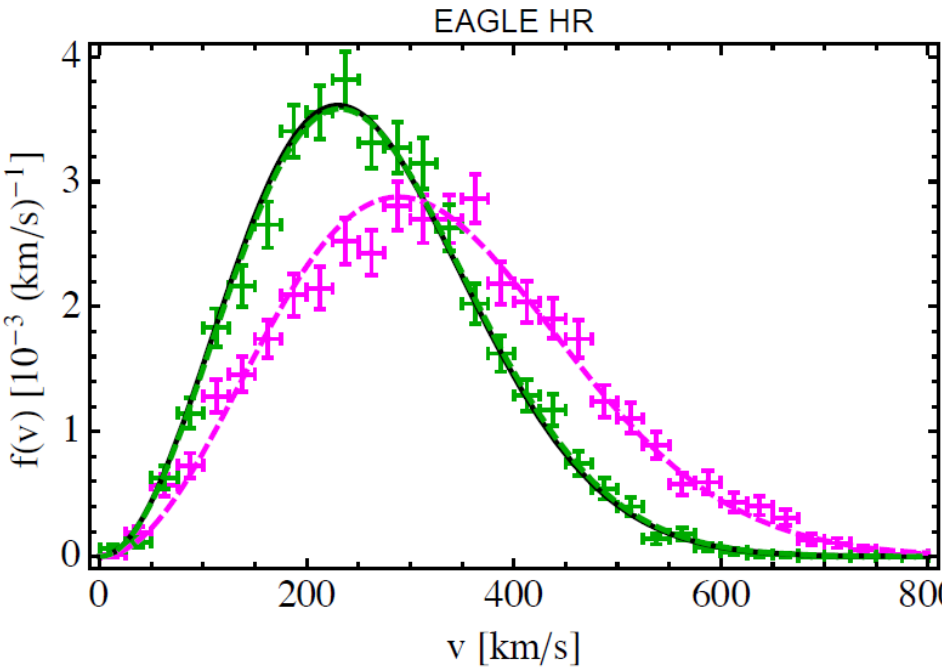
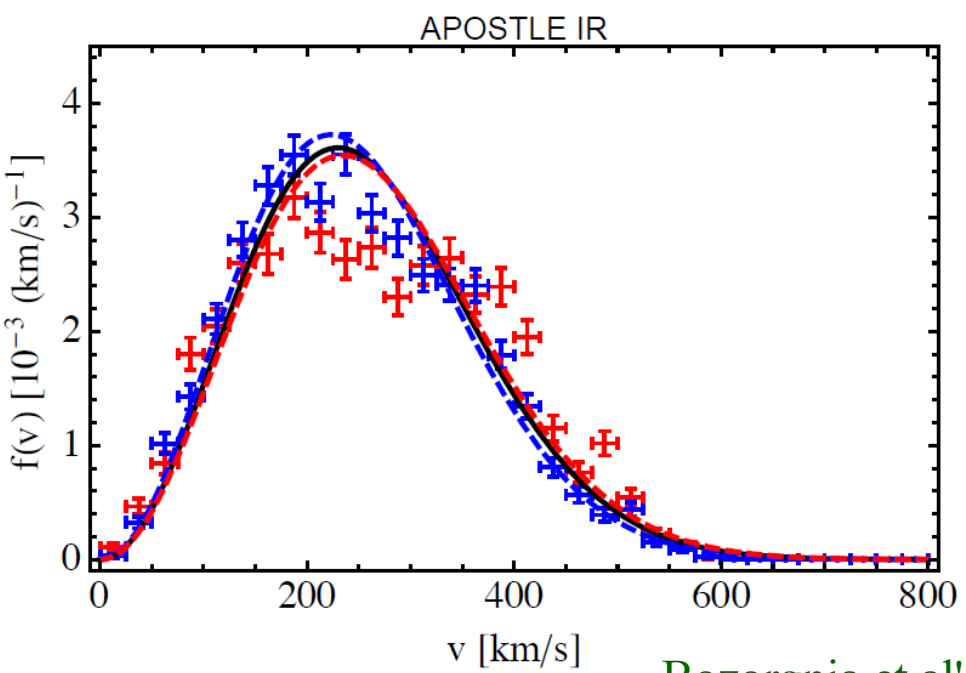
  - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.
  - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann
  - Hydrodynamical simulations (DM+baryons). Inconclusive at the moment.



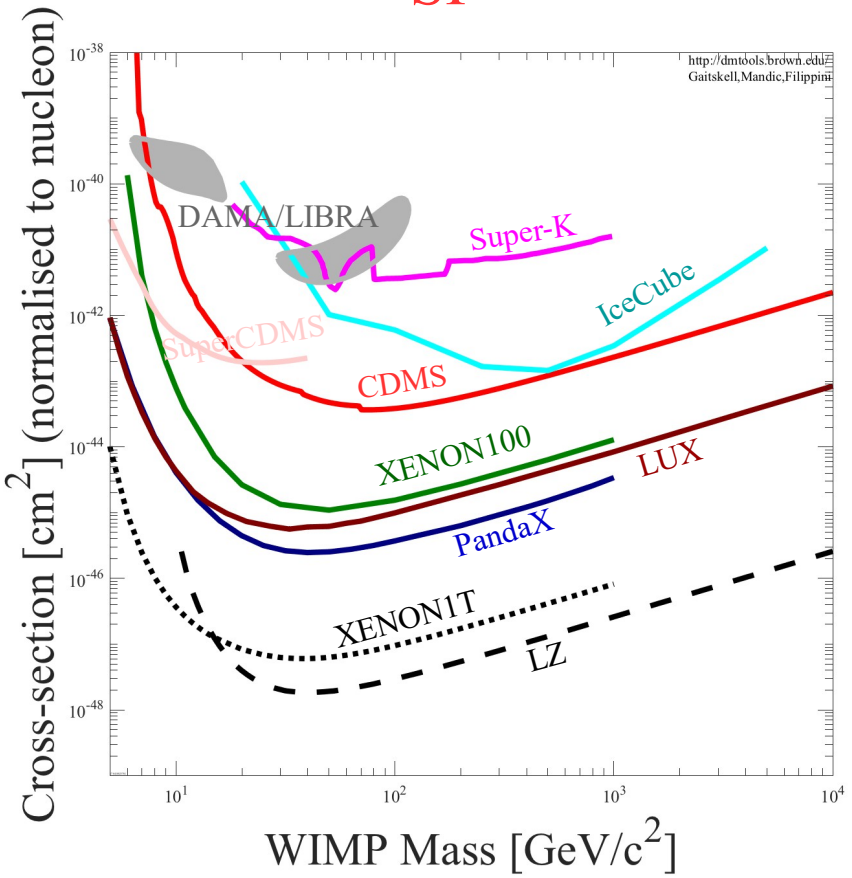


Bozorgnia et al'16

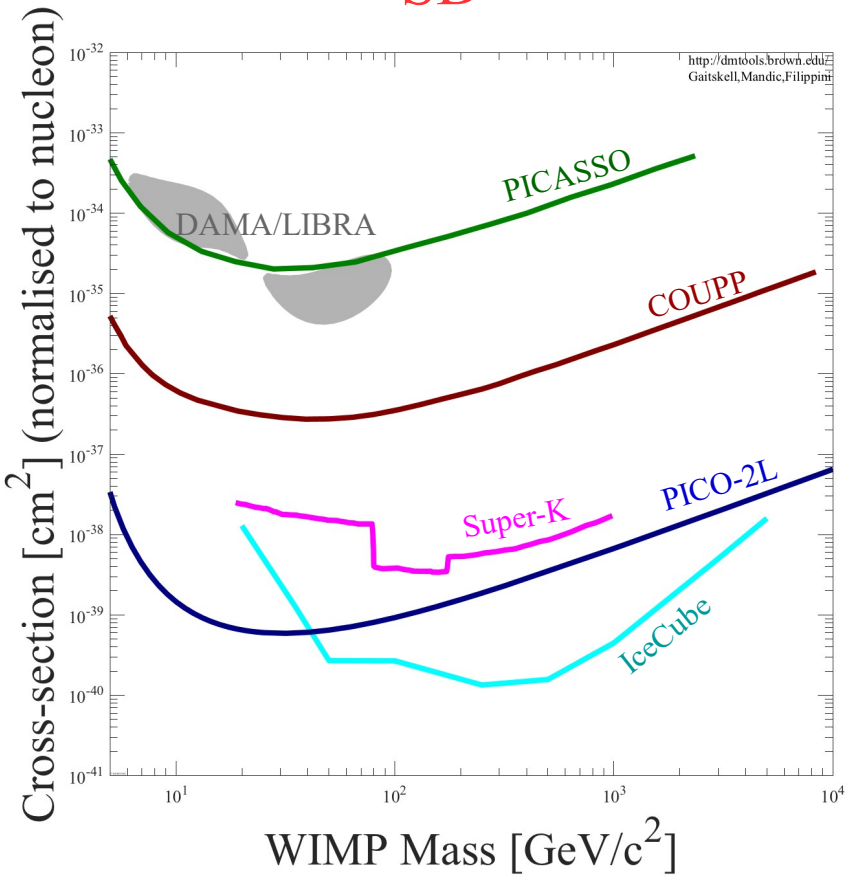
Theoretical interpretation of the experimental results

Common approach: assume SI or SD interaction only, assume $\rho_{loc} = 0.3$ GeV/cm^3 and assume a Maxwell-Boltzmann velocity distribution

SI



SD



Theoretical interpretation of the experimental results

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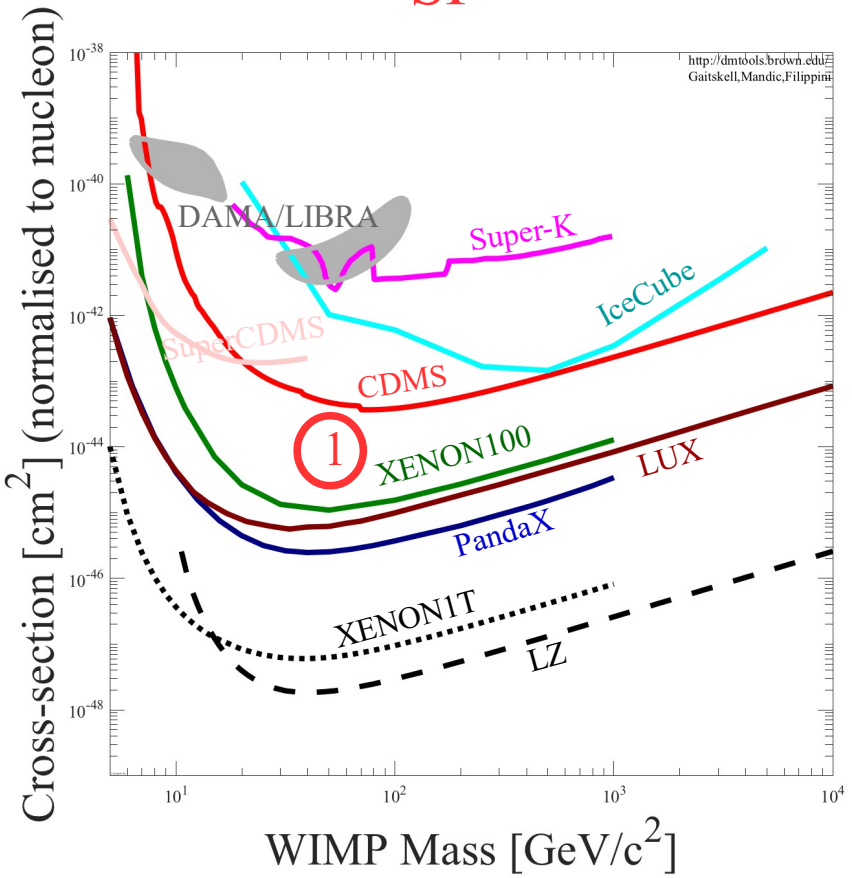
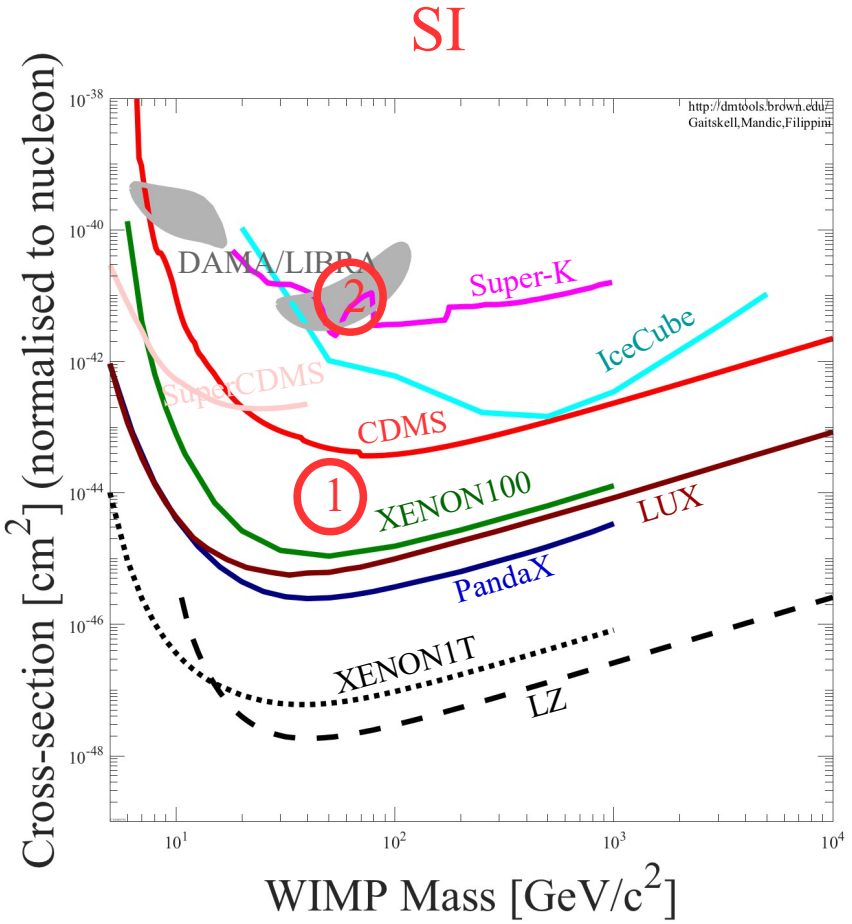
SI



1 is ruled out (by PandaX, among others)

Theoretical interpretation of the experimental results

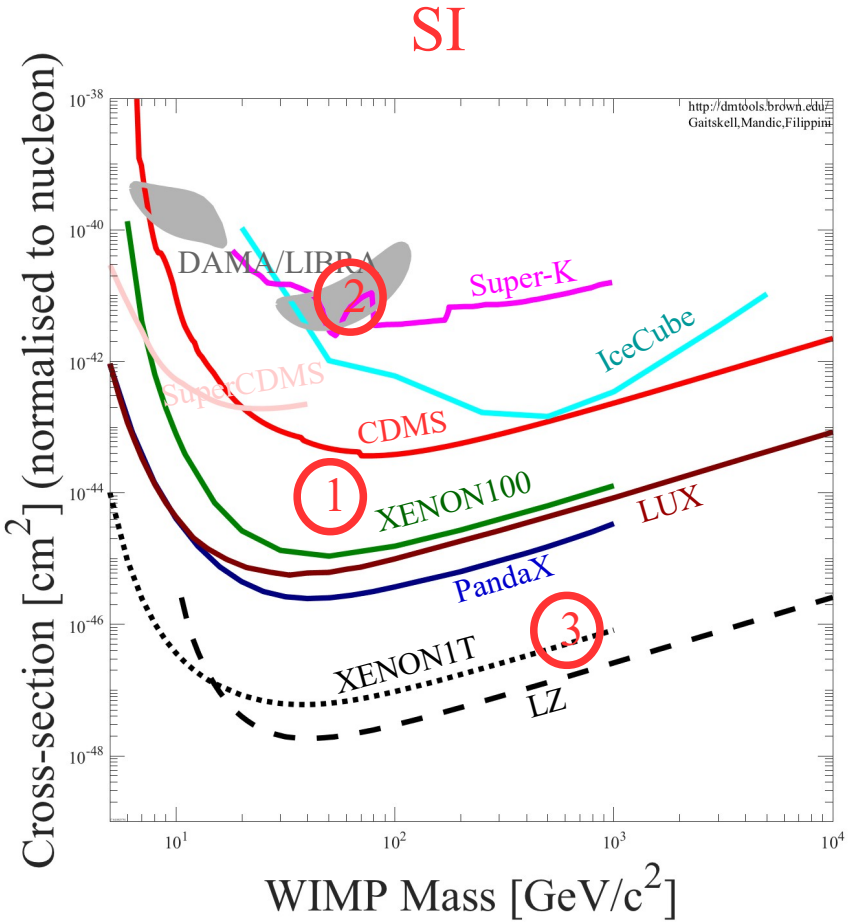
Common approach: assume SI or SD interaction only, assume $\rho_{loc} = 0.3$ GeV/cm^3 and assume a Maxwell-Boltzmann velocity distribution



1. is ruled out (by PandaX, among others)
2. explains the DAMA results, but is ruled out by other direct detection experiments and by neutrino telescopes

Theoretical interpretation of the experimental results

Common approach: assume SI or SD interaction only, assume $\rho_{loc} = 0.3$ GeV/cm^3 and assume a Maxwell-Boltzmann velocity distribution



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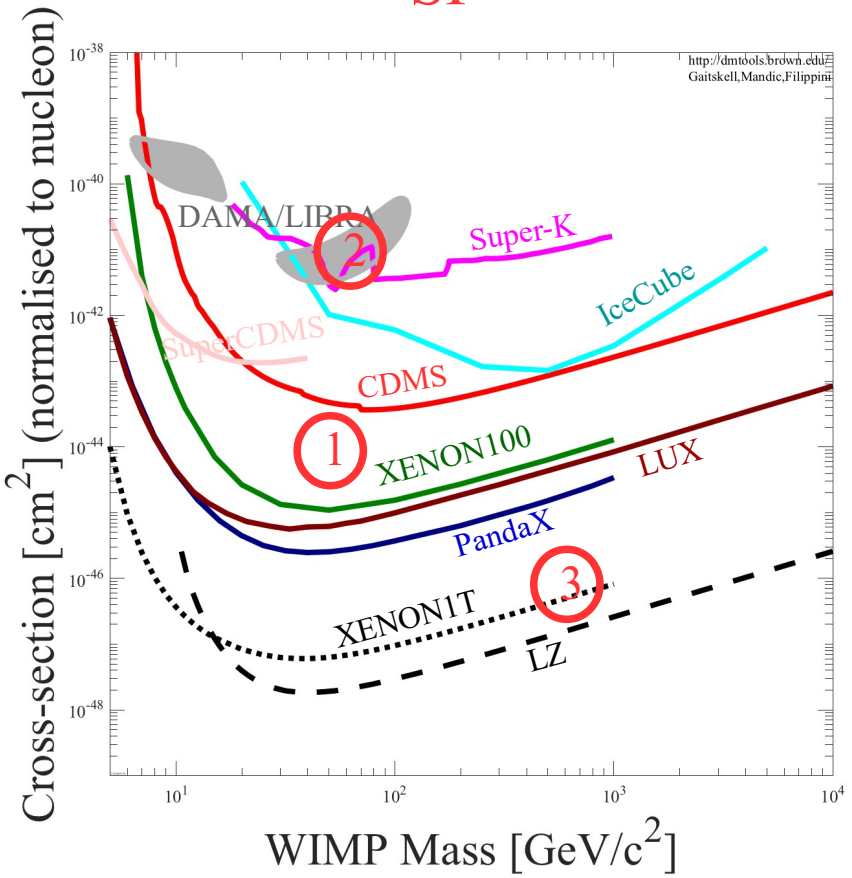
2. explains the DAMA results, but is ruled out by other direct detection experiments and by neutrino telescopes

3. is allowed by current experiments, and will be tested by LZ.

Theoretical interpretation of the experimental results

Common approach: assume SI or SD interaction only, assume $\rho_{loc} = 0.3$ GeV/cm^3 and assume a Maxwell-Boltzmann velocity distribution

SI



1. is ruled out (by PandaX, among others)
2. explains the DAMA results, but is ruled out by other direct detection experiments and by neutrino telescopes
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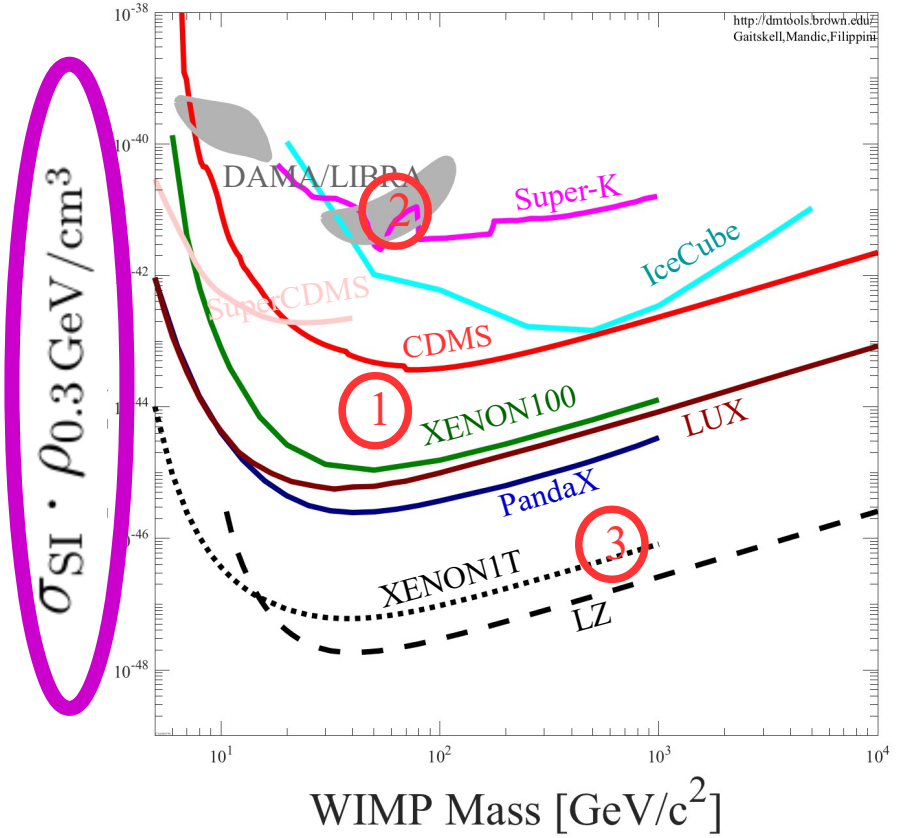
What is the impact of the astrophysical uncertainties?

Theoretical interpretation of the experimental results

Common approach: assume SI or SD interaction only, assume $\rho_{loc} = 0.3$ GeV/cm^3 and assume a Maxwell-Boltzmann velocity distribution

SI



1. is ruled out (by PandaX, among others)
2. explains the DAMA results, but is ruled out by other direct detection experiments and by neutrino telescopes
3. is allowed by current experiments, and will be tested by LZ.

What is the impact of the astrophysical uncertainties?

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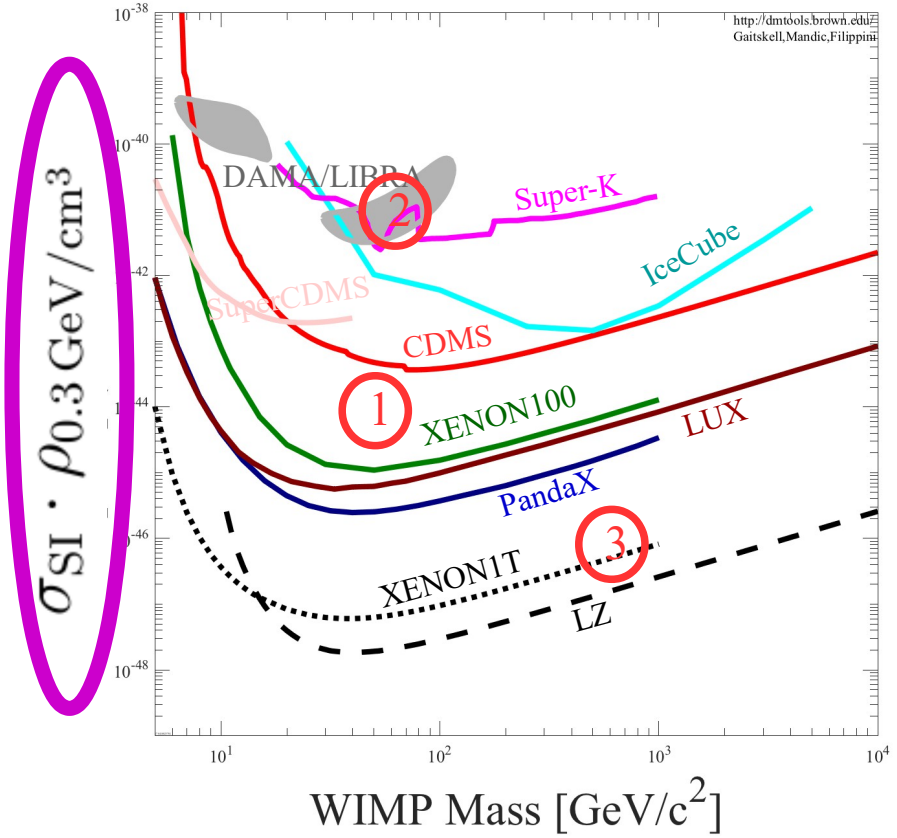

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What is the impact of the astrophysical uncertainties?

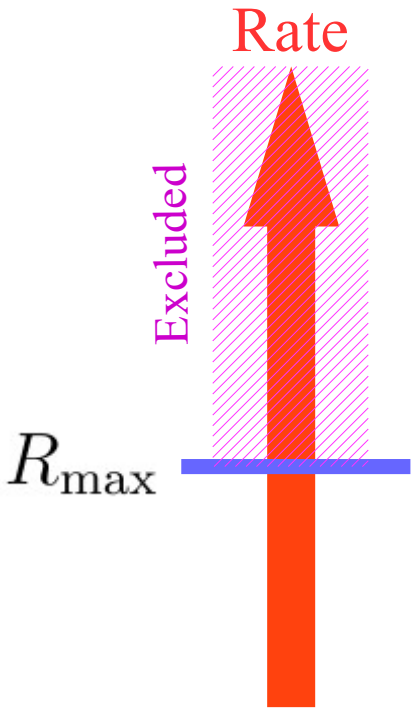
Do these conclusions hold for arbitrary velocity distributions?

Addressing astrophysical uncertainties in dark matter detection

Halo-independent approach for DM frameworks

- $(\sigma, m_{\rm DM})$ is ruled out regardless of the velocity distribution if

$$\min_{f(\vec{v})} \left\{ R(\sigma, m_{\rm DM}) \right\} > R_{\rm max}$$



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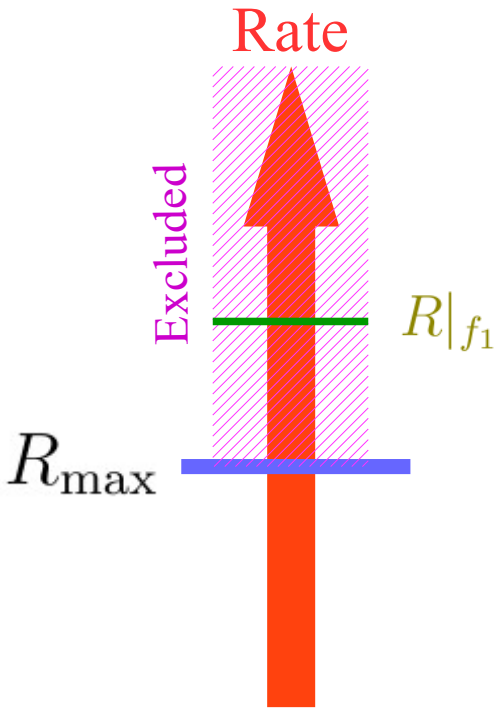

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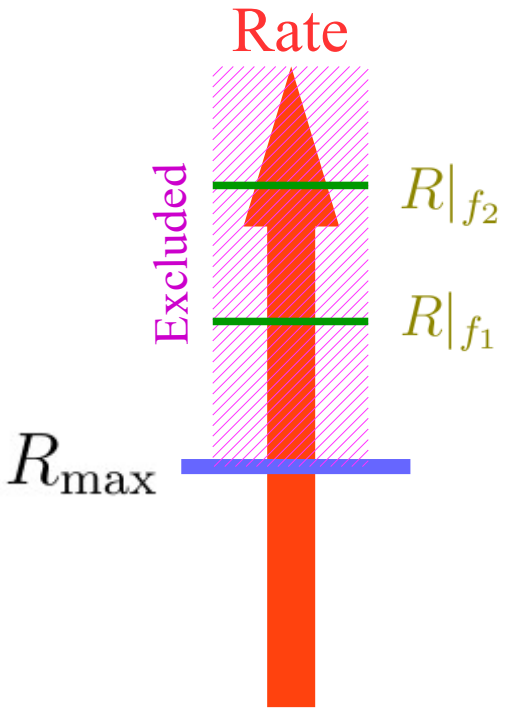

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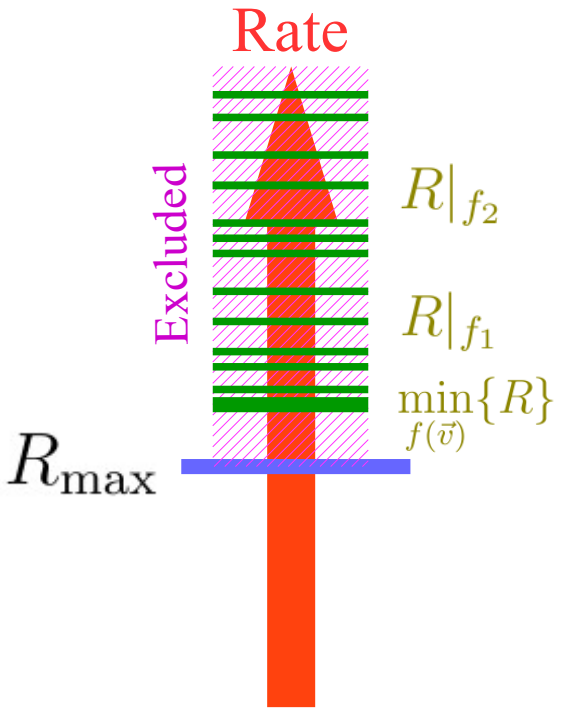

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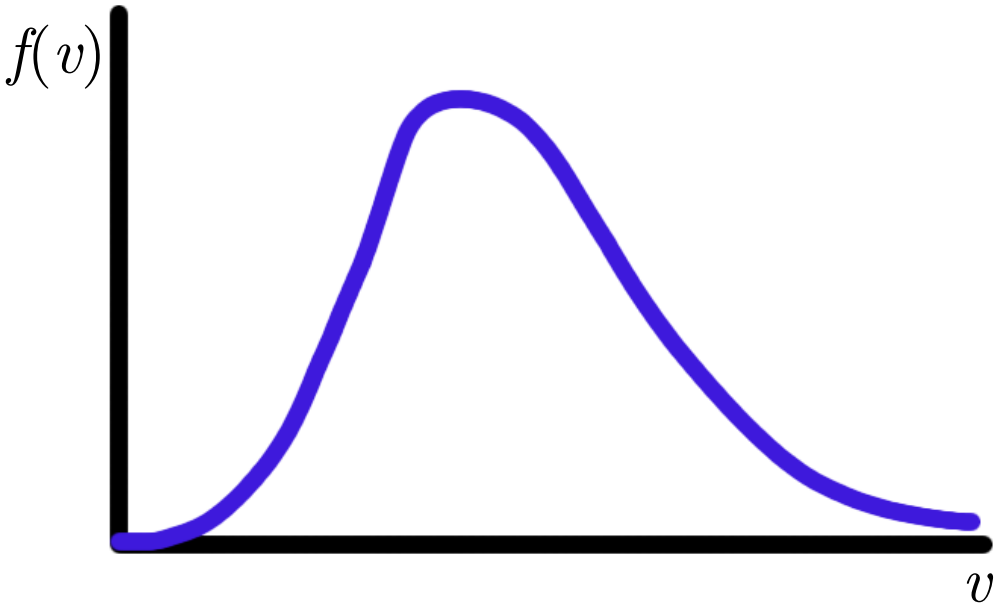
Note: one single direct detection experiment is not sufficient to probe a dark matter model in a halo-independent manner



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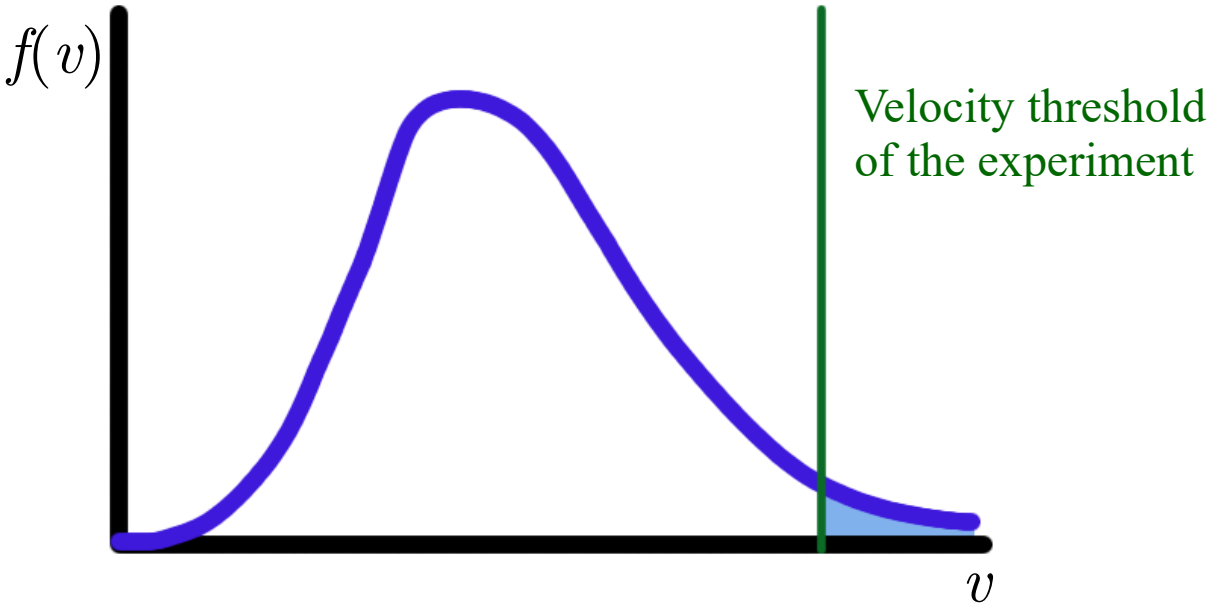

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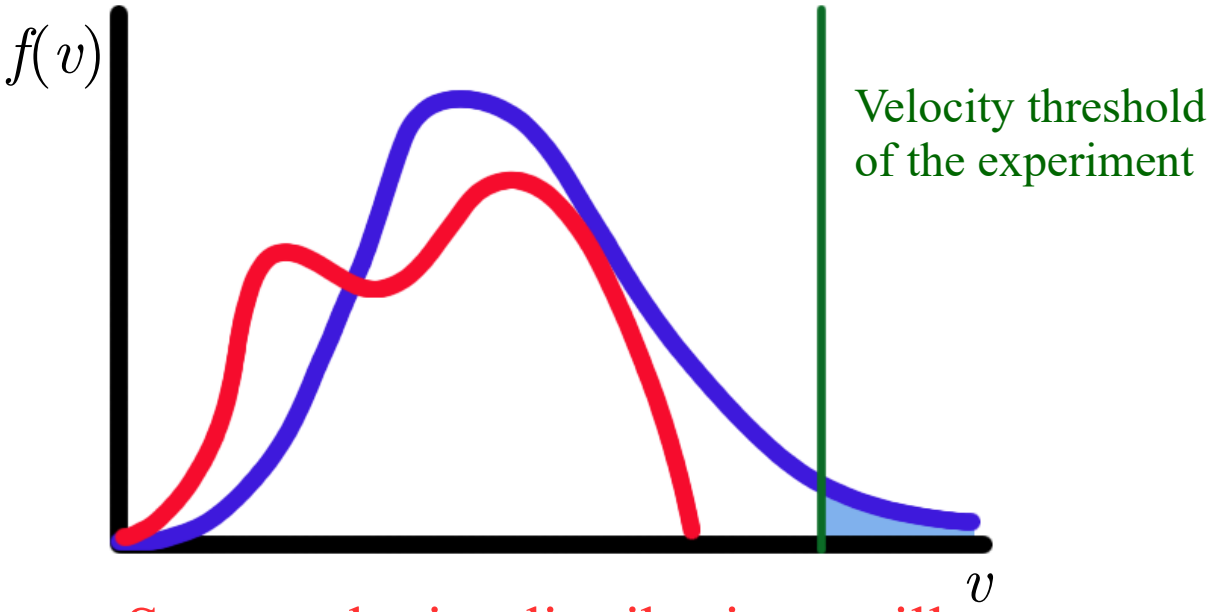

Some velocity distributions will escape detection in the experiment

Halo-independent approach for DM frameworks

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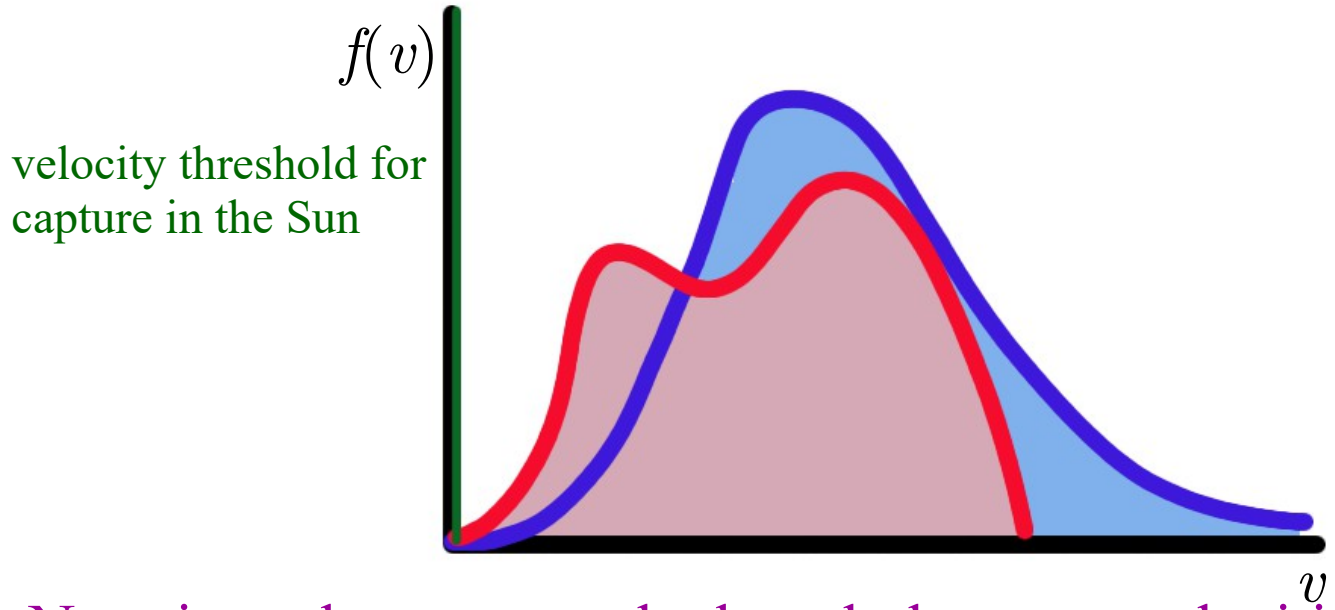

Neutrino telescopes probe low dark matter velocities. In combination with direct detection experiments, one can probe the whole velocity space

Halo-independent approach for DM frameworks

- $(\sigma, m_{\rm DM})$ is ruled out regardless of the velocity distribution if

$$\min_{f(\vec{v})} \left\{ R(\sigma, m_{\rm DM}) \right\} > R_{\rm max}$$

$$\min_{f(\vec{v})} \left\{ R(\sigma, m_{\rm DM}) \right\} \Big|_{\substack{C(\sigma,m) \leq C_{\rm max} \\ \int f = 1}} > R_{\rm max}$$

Optimization problem with constraints

Halo-independent approach for DM frameworks

Technically complicated...

$$R(\sigma, m_{\rm DM}) = \int_{E_{\rm th}}^{\infty} dE_R \frac{\rho_{\rm loc}}{m_A m_{\rm DM}} \int_{v \geq v_{\rm min}(E_R)} {\rm d}^3 v \, v f(\vec{v} + \vec{v}_{\rm obs}(t)) \frac{{\rm d}\sigma}{{\rm d}E_R}$$

$$C(\sigma, m_{\rm DM}) = \int_0^{R_\odot} 4\pi r^2 {\rm d}r \, \frac{\rho_{\rm loc}}{m_{\rm DM}} \int_{v \leq v_{\rm max}^{\rm (Sun)}(r)} {\rm d}^3 v \, \frac{f(\vec{v})}{v} \left(v^2 + [v_{\rm esc}(r)]^2\right) \times \int_{m_{\rm DM} v^2/2}^{2\mu_A^2 \left(v^2 + [v_{\rm esc}(r)]^2\right)/m_A} {\rm d}E_R \frac{{\rm d}\sigma}{{\rm d}E_R}$$

Halo-independent approach for DM frameworks

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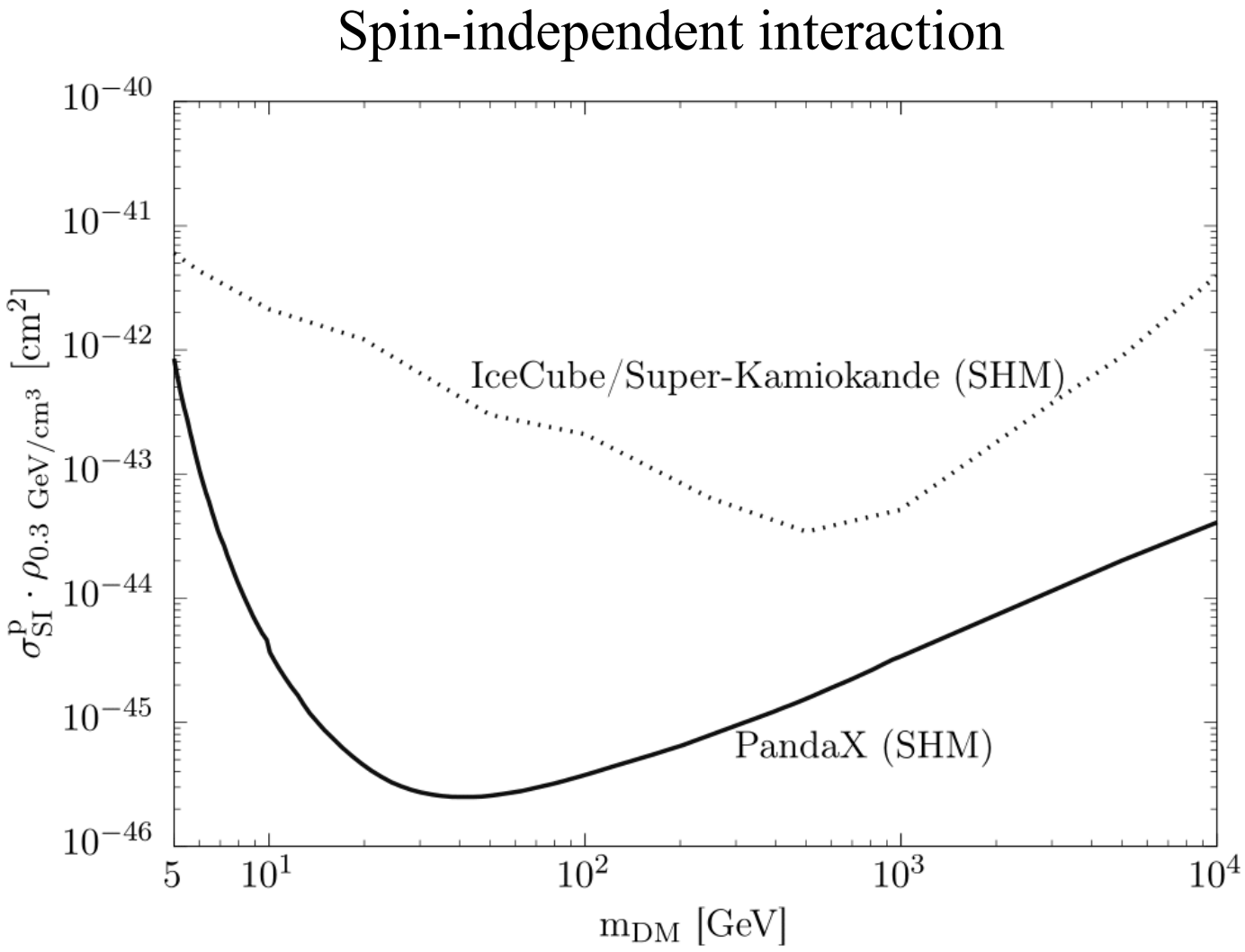
Take-home result:

The velocity distribution that minimizes the rate is composed by a number of dark matter "streams", at most as many as constraints.

Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.



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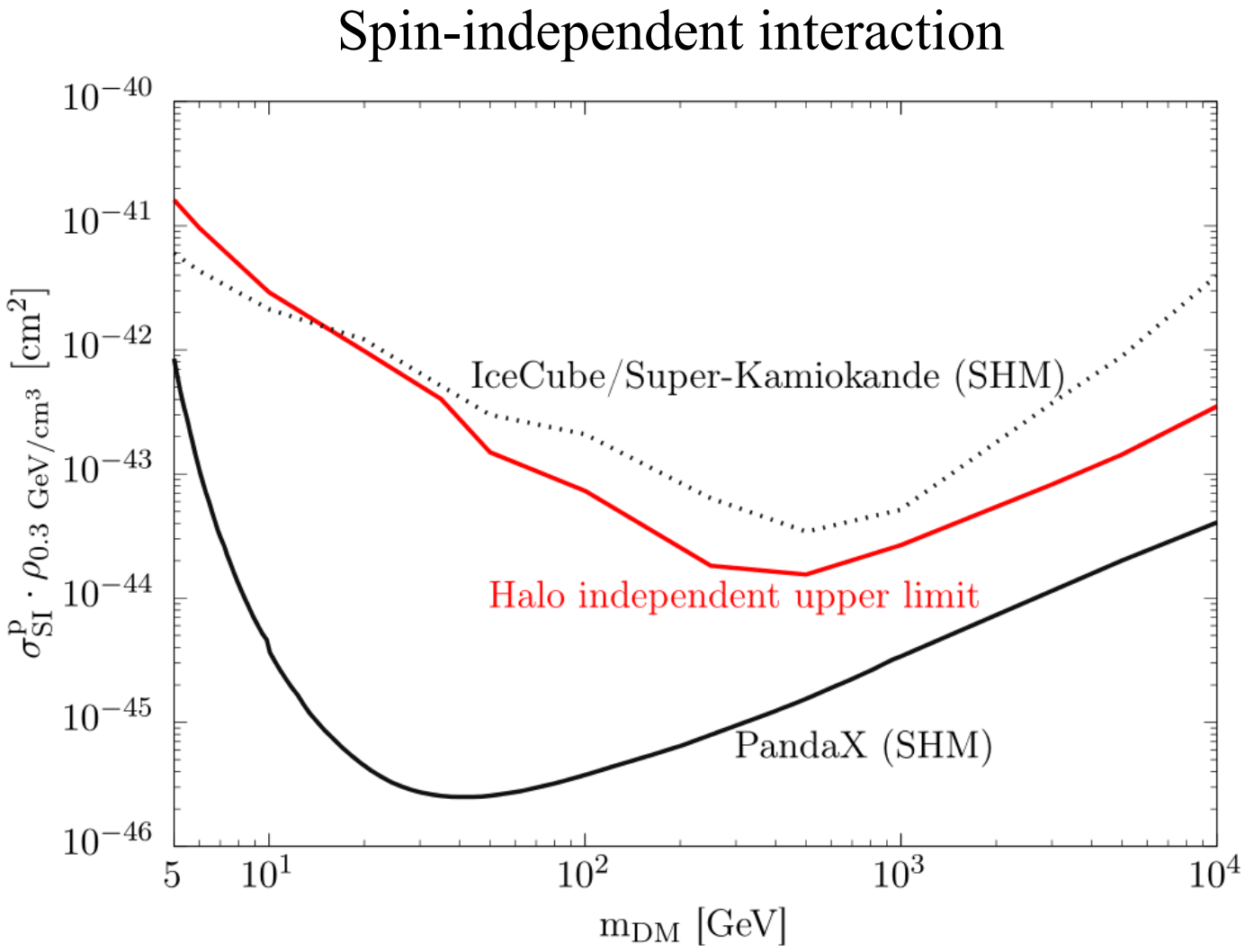
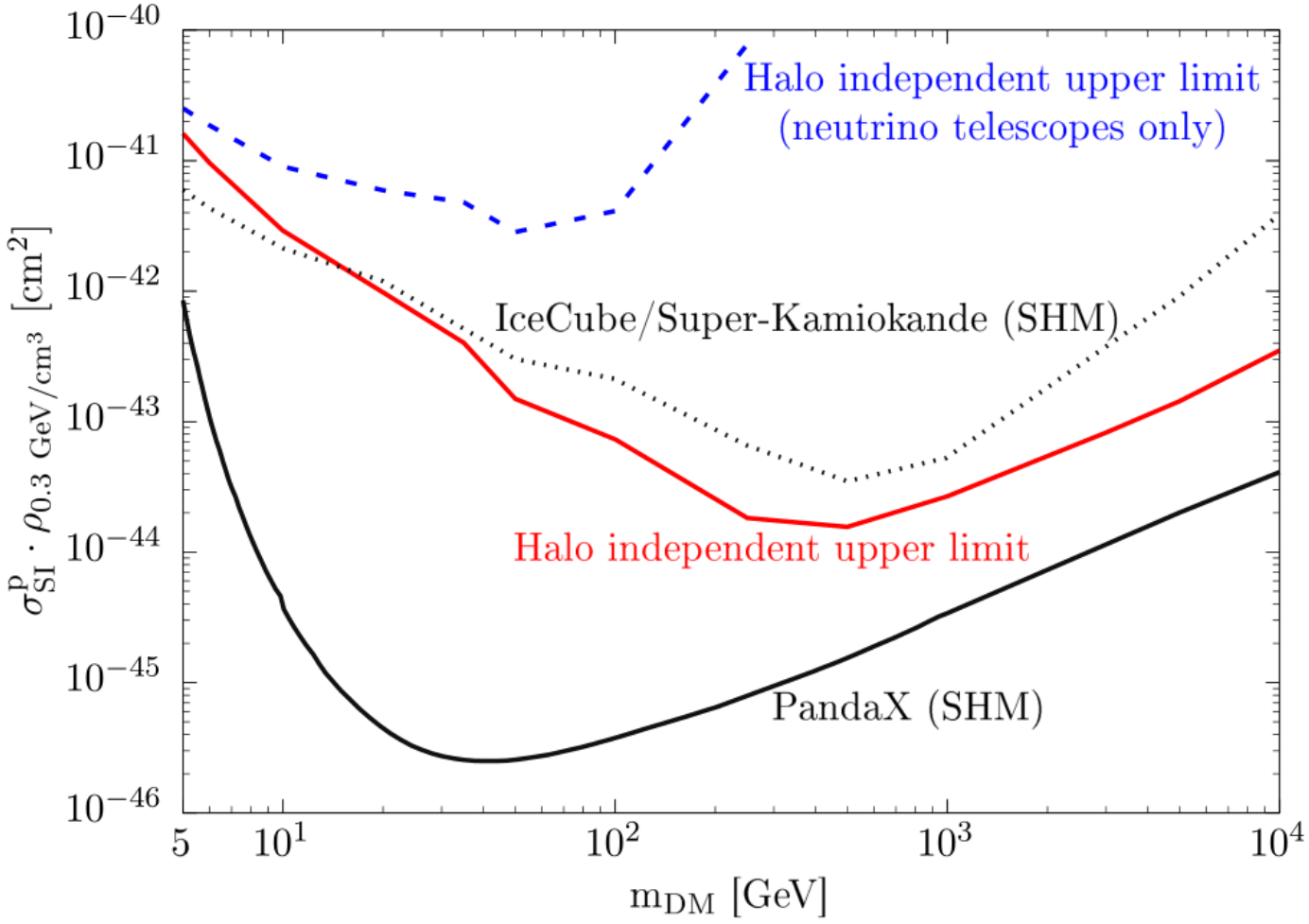


The optimal velocity distribution corresponds to a superposition of two dark matter streams.

Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Spin-independent interaction



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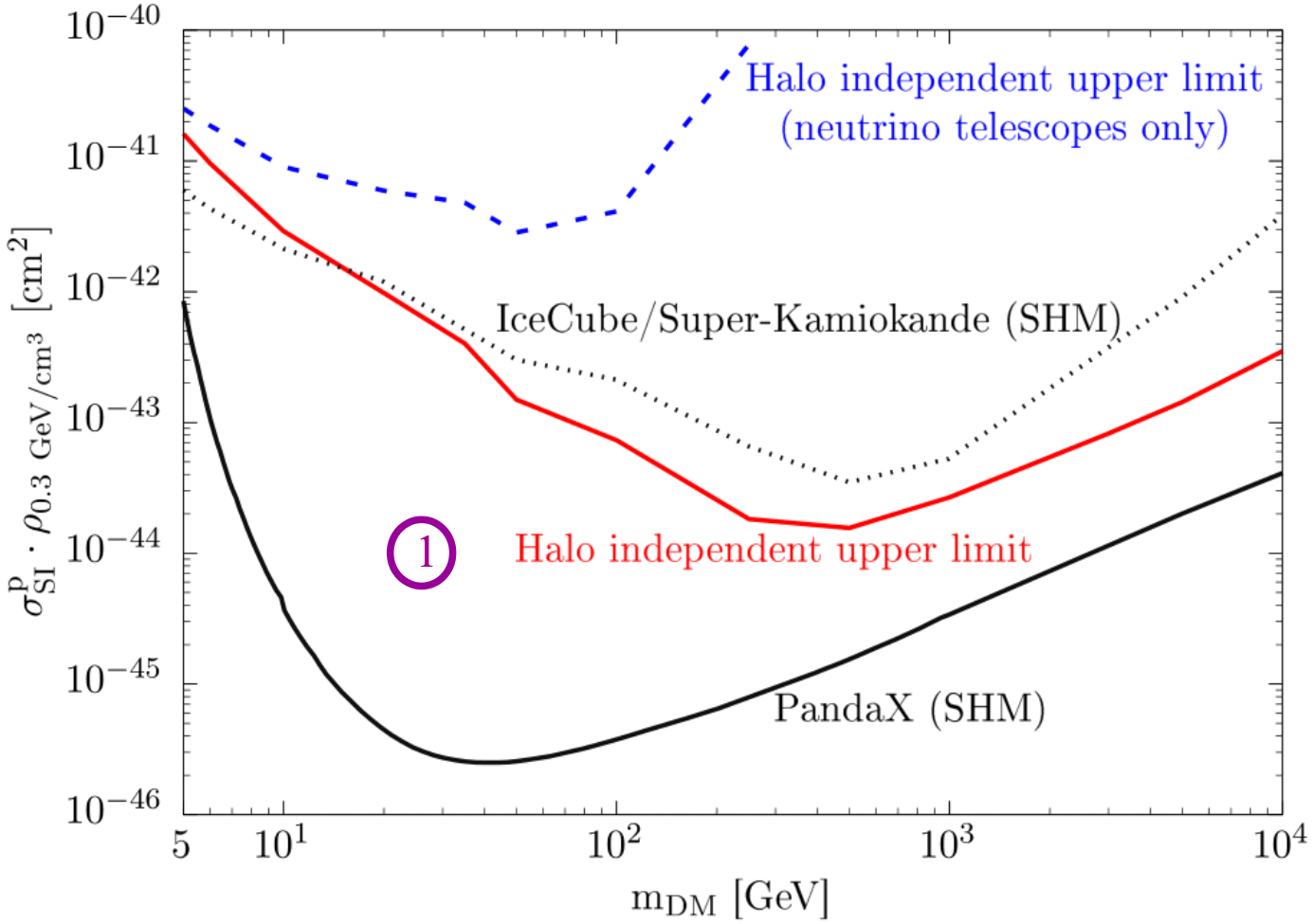

1 is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions

Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

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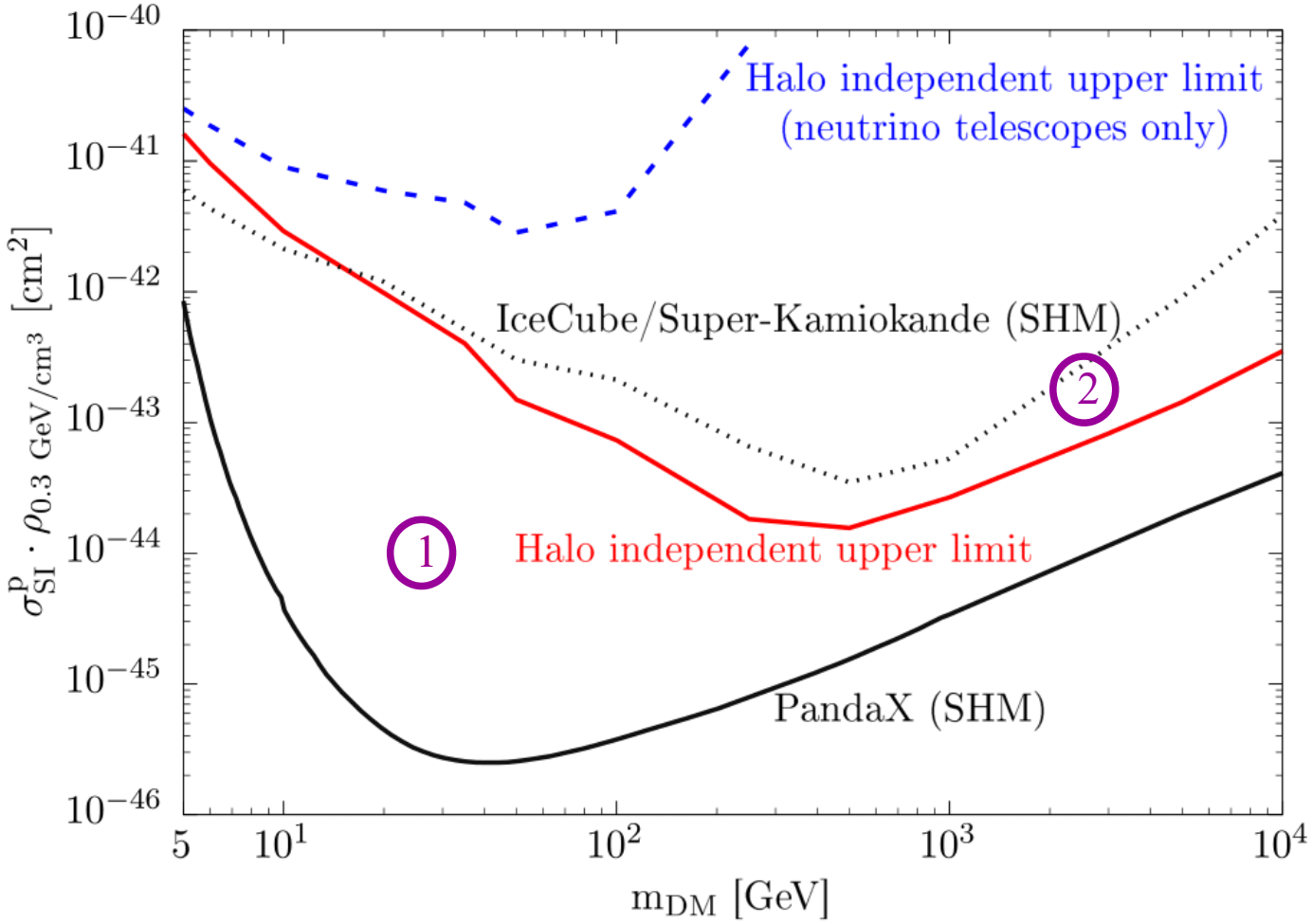
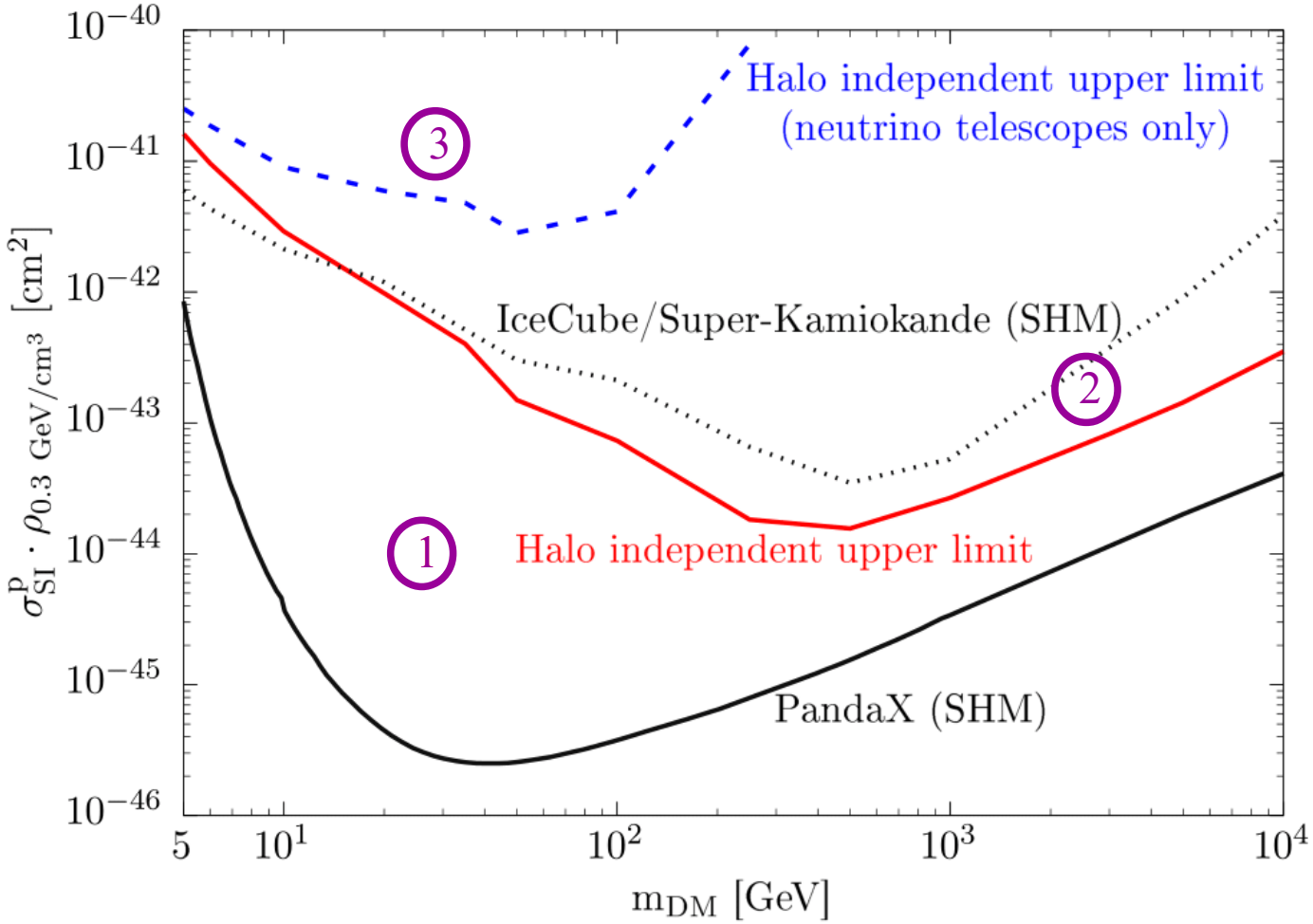


(1) is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions

(2) is ruled out from combining PandaX and neutrino telescopes, for *any* velocity distribution.

Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Spin-independent interaction



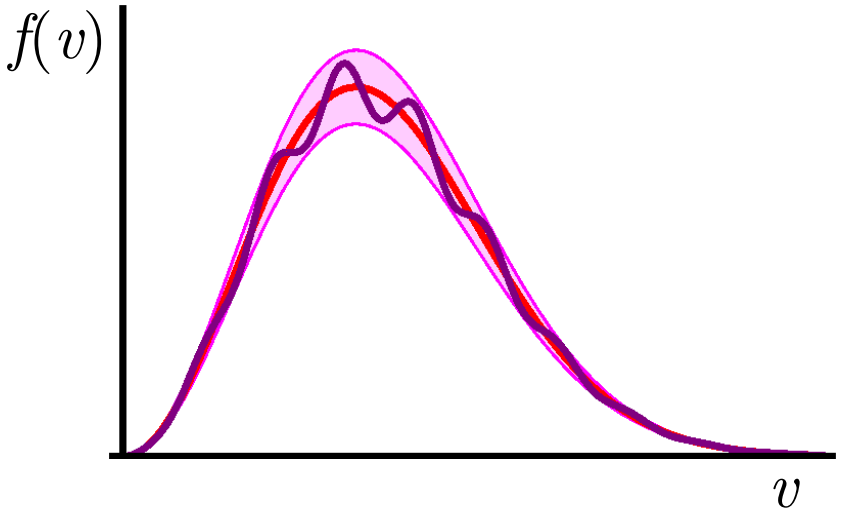
1 is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions

2 is ruled out from combining PandaX and neutrino telescopes, for *any* velocity distribution.

3 is ruled out by neutrino telescopes only, for *any* velocity distribution.

Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

It is unlikely that the halo independent upper limit saturates (it is unlikely that the velocity distribution consists just of two streams). Add physically plausible assumptions (e.g. MB distribution + "distortions").



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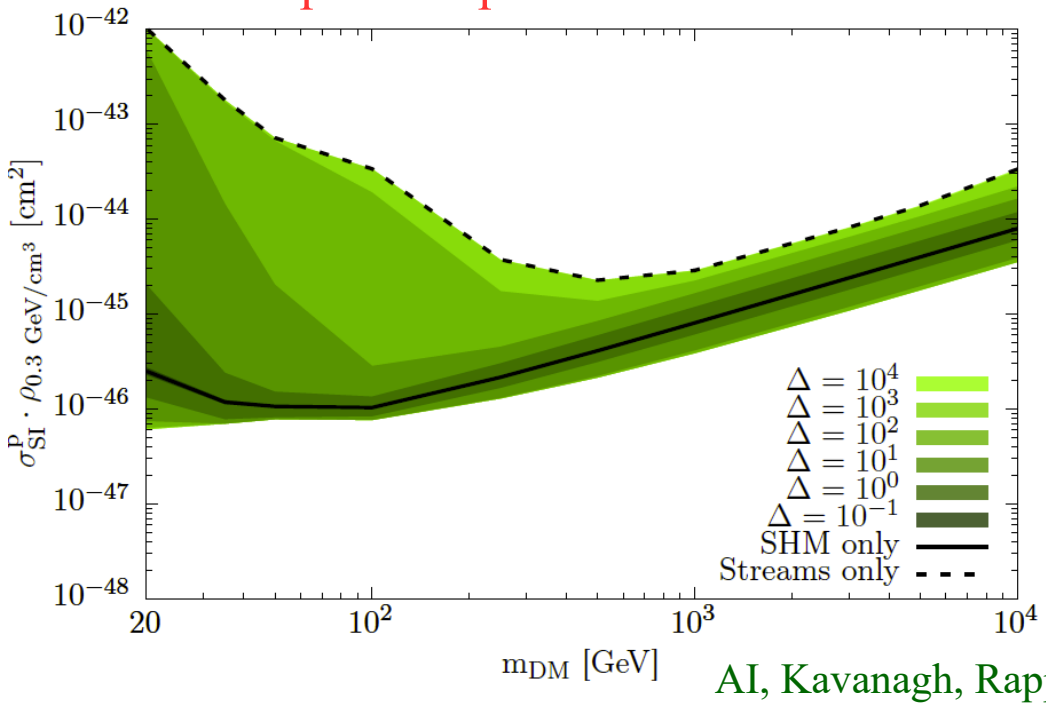


AI, Kavanagh, Rappelt
To appear

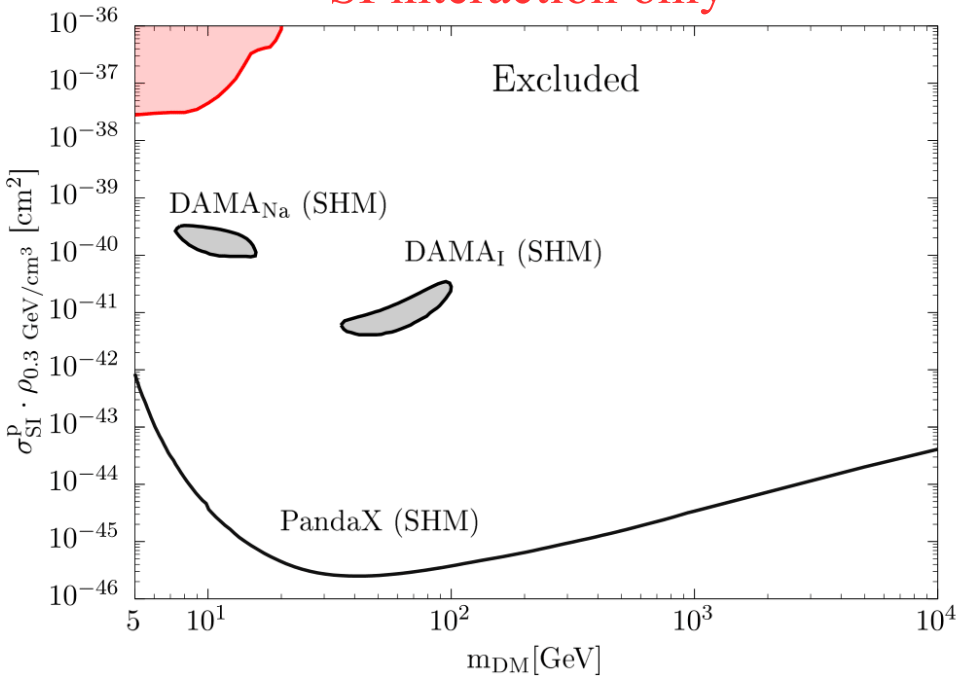
DAMA confronted to null results in a halo independent way

Strategy: minimize the rate at a given experiment, with the constraints that the modulation signal at DAMA in the bins [2.0,2.5], [2.5,3.0] and [3.0,3.5] keV are as reported by the experiment.

The parameters σ and m_{DM} are excluded in a halo independent manner if:

$$\min_{f(\vec{v})} \left\{ R^{(\mathrm{PandaX})}(\sigma, m_{\mathrm{DM}}) \right\} \Big|_{\mathrm{constraints}} \geq R^{(\mathrm{PandaX})}_{\mathrm{max}}$$

SI interaction only



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$$\min_{f(\vec{v})} \left\{ C^{(\mathrm{NT})}(\sigma, m_{\mathrm{DM}}) \right\}\Big|_{\mathrm{constraints}} \geq C^{(\mathrm{NT})}_{\mathrm{max}}$$

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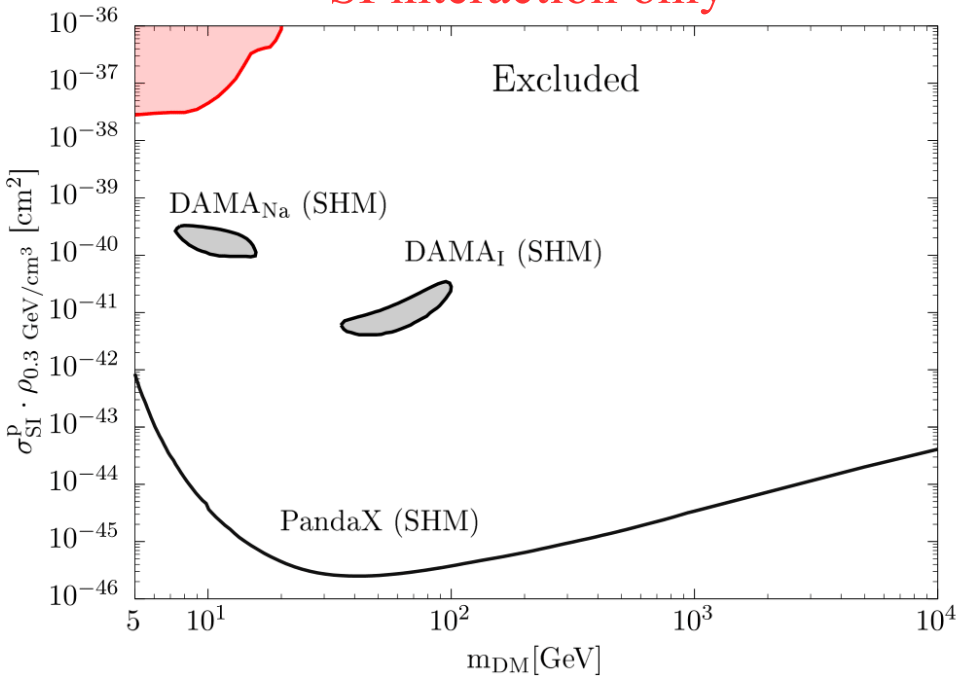

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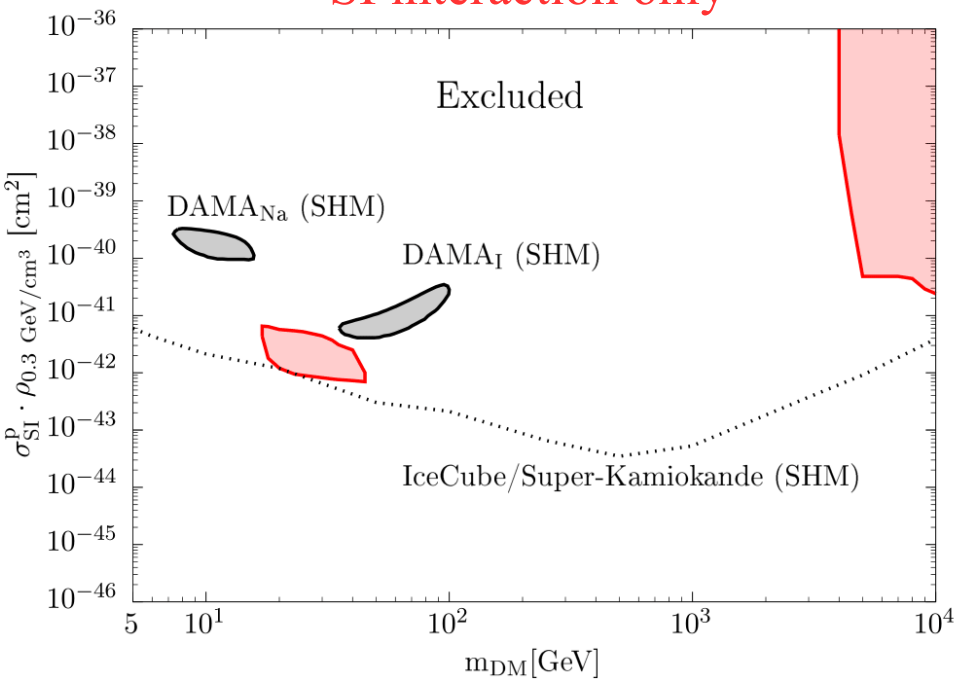


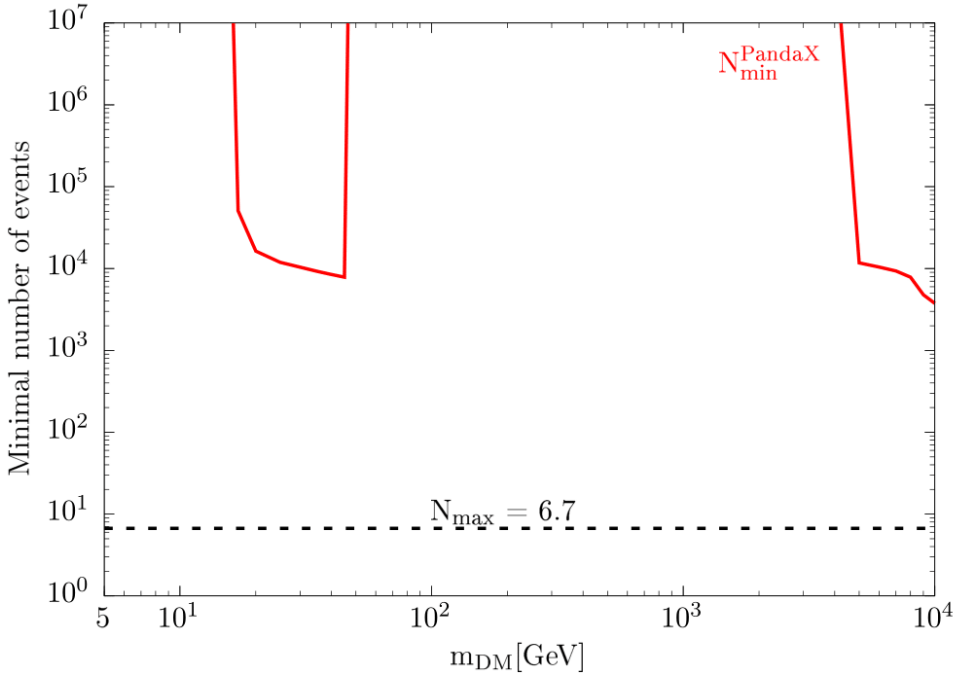
DAMA confronted to null results in a halo independent way

Strategy 2: minimize the rate at a given direct detection experiment, with the constraints that the modulation signal at DAMA in the bins [2.0,2.5], [2.5,3.0] and [3.0,3.5] keV are as reported by the experiment, and the capture rate at IceCube is below the current upper limit.

The parameters σ and m_{DM} are excluded in a halo independent manner if:

$$\min_{f(\vec{v})} \left\{ R^{(\mathrm{PandaX})}(\sigma, m_{\mathrm{DM}}) \right\} \Big|_{\mathrm{constraints}} \geq R^{(\mathrm{PandaX})}_{\mathrm{max}}$$

SI interaction only



At least 3000 events expected at Panda-X

AI, Rappelt '17

Halo independent prospects for future experiments

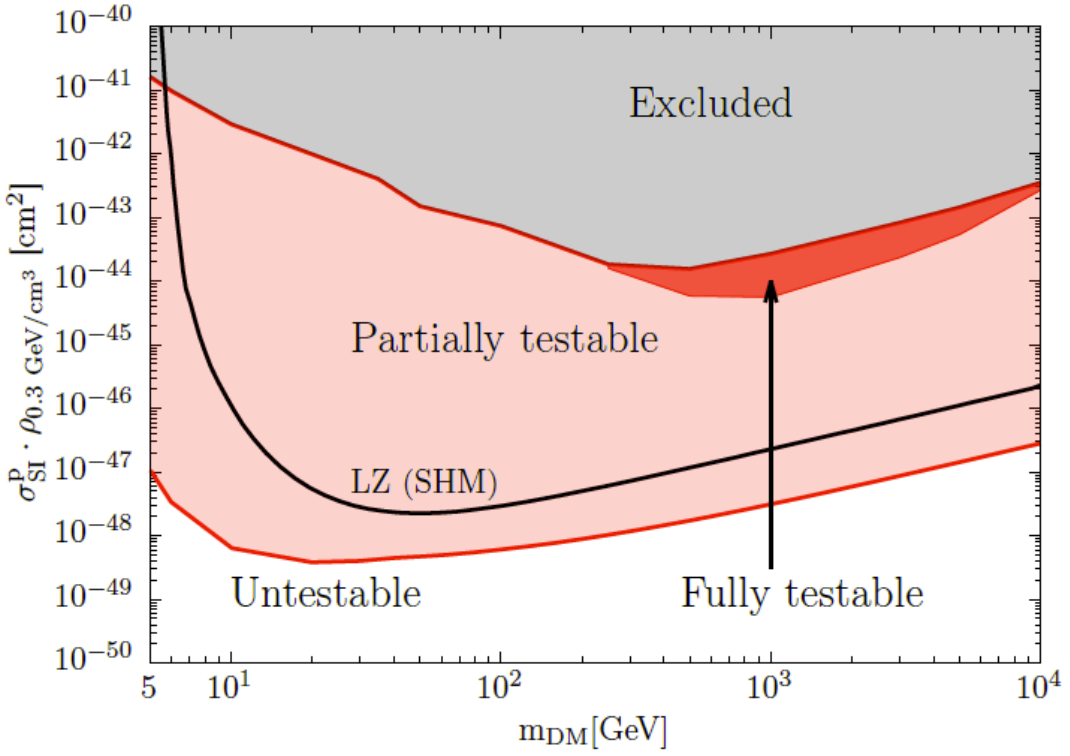
The parameters σ and m_{DM} are fully testable in a halo independent manner if :

$$\min_{f(\vec{v})} \left\{ R^{(\mathrm{LZ})}(\sigma, m_{\mathrm{DM}}) \right\} \Big|_{\mathrm{constraints}} > 1$$

The parameters σ and m_{DM} are untestable in a halo independent manner if :

$$\max_{f(\vec{v})} \left\{ R^{(\mathrm{LZ})}(\sigma, m_{\mathrm{DM}}) \right\} \Big|_{\mathrm{constraints}} < 1$$

LZ reach to the SI cross-section from null results at neutrino telescopes



Conclusions

- The interpretation of any experiment probing the dark matter distribution inside the Solar System is subject to our ignorance of the local dark matter density and velocity distribution.

- We have developed a method to calculate the minimum/maximum number of signal events in an experiment probing the dark matter distribution inside the Solar System, in view of a number of constraints from direct detection experiments and/or neutrino telescopes.

- Some applications are:

  i) to derive a halo-independent upper limit on the cross section from a set of null results.
  ii) to confront in a halo-independent way a detection claim to a set of null results.
  iii) to assess, in a halo-independent manner, the prospects for detection in a future experiment given a set of current null results.

- The method could be extended to include other dark matter interactions, or to account for more realistic velocity configurations.

Upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Express the velocity distribution as a superposition of many many streams:

$$f(\vec{v}) = \sum_{i=1}^{n} c_{\vec{v}_i}\ \delta(\vec{v} - \vec{v}_i)$$

Minimization problem. For given DM mass and cross-section:

$$\text{minimize}\quad R^{(\text{PandaX})}(c_{\vec{v}_1}\ldots, c_{\vec{v}_n}) = \sum_{i=1}^{n} c_{\vec{v}_i} R^{(\text{PandaX})}_{\vec{v}_i}\ ,$$

$$\text{subject to}\quad \sum_{i=1}^{n} c_{\vec{v}_i} C^{(\text{NT})}_{\vec{v}_i} \leq C^{(\text{NT})}_{\text{max}},$$

$$\text{and}\quad \sum_{i=1}^{n} c_{\vec{v}_i} = 1\ ,$$

$$\text{and}\quad c_{\vec{v}_i} \geq 0,\quad i = 1\ldots, n\ ,$$

The parameters σ and m_{DM} are excluded in a halo independent manner if :

$$\min\left\{R^{(\text{PandaX})}(c_{\vec{v}_1}\ldots, c_{\vec{v}_n})\right\}\Big|_{\text{constraints}} > R^{(\text{PandaX})}_{\text{max}}$$

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$$\text{and}\quad c_{\vec{v}_i} \geq 0, \quad i = 1..., n\ ,$$

The objective function and the constraints are linear in the weights of the DM streams

↪ Optimize using linear programming techniques.

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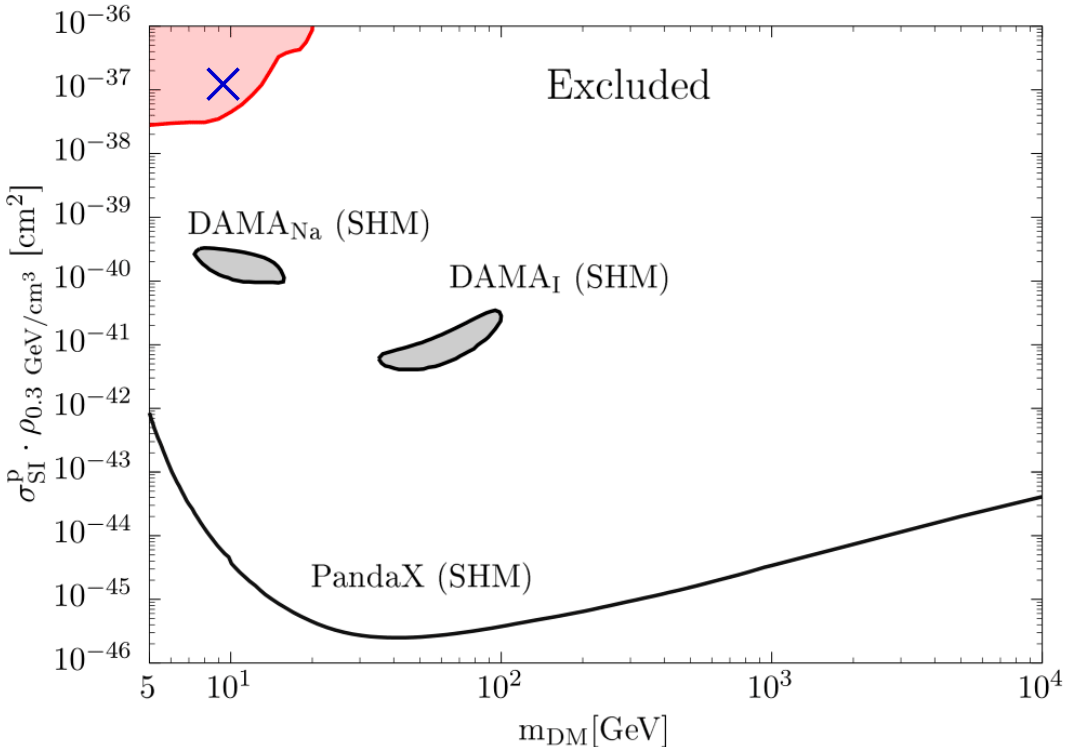
$$\text{and}\quad c_{\vec{v}_i} \geq 0,\quad i = 1\ldots, n\ ,$$

1) The solution lies at one of the vertices of the "feasible region"

2) The optimized velocity distribution contains either one or two streams (depending on the number of constraints that are not saturated).

DAMA confronted to null results

1) DAMA confronted to PandaX (SI interaction only)



	stream #1	stream #2	stream #3	stream #4
$c_{\vec{v}_i}$	0.54	0.28	0.18	–
$\vec{v}_i$ [km/s]	$(-10, -123, 191)$	$(100, -167, -161)$	$(56, 119, -183)$	–
$\lvert\vec{v}_{i,\max}^{(\mathrm{PandaX})}\rvert$ [km/s]	257.1	264.3	255.1	–
$\lvert\vec{v}_{i,\mathrm{June}}^{(\mathrm{DAMA})}\rvert$ [km/s]	256.1	245.0	195.7	–
$\lvert\vec{v}_{i,\mathrm{Dec}}^{(\mathrm{DAMA})}\rvert$ [km/s]	198.8	263.2	255.1	–

For $m_{\mathrm{DM}} = 10$ GeV, $v_{\min}^{(\mathrm{PandaX})} = 259.6\,\mathrm{km/s}$ and $v_{\min}^{(\mathrm{DAMA[3.0,3.5]})} = 143.9\,\mathrm{km/s}$.